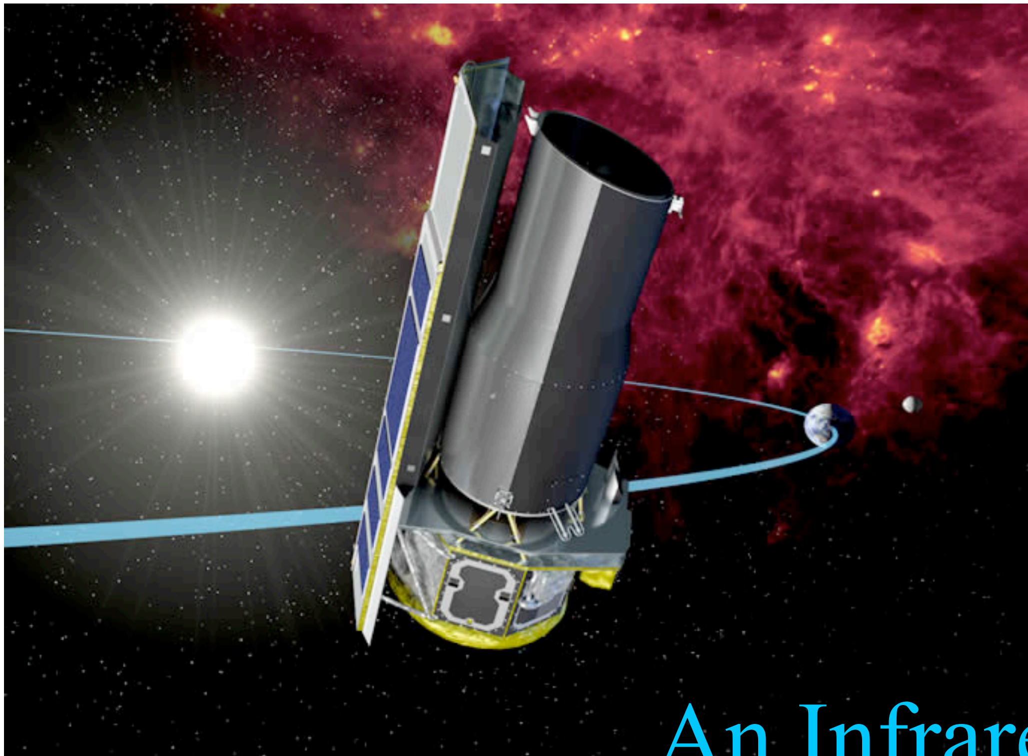
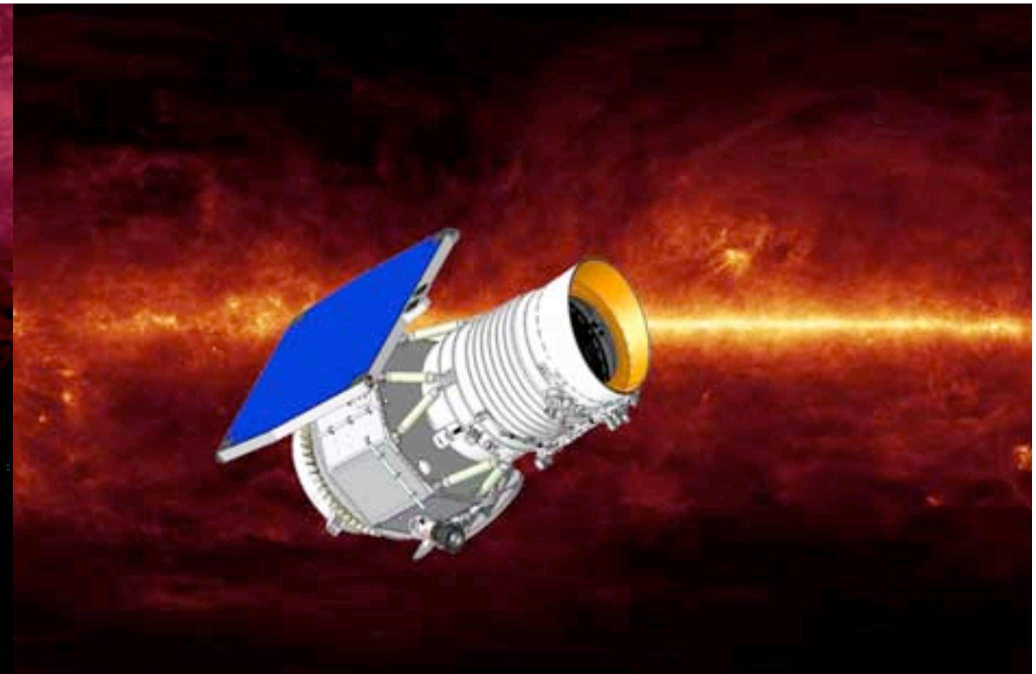




An Infrared View of Galaxy Clusters at High Redshift

Anthony Gonzalez

University of Florida

Daniel Gettings

In collaboration with:

Conor Mancone
Daniel Gettings
Adam Stanford
Mark Brodwin
Peter Eisenhardt
Cosimo Fedeli
Daniel Stern
Arjun Dey

Greg Snyder
Greg Zeimann
Buell Jannuzi
Leonidas Moustakas
Tom Plagge
John Carlstrom
Marshall Joy
Erik Leitch

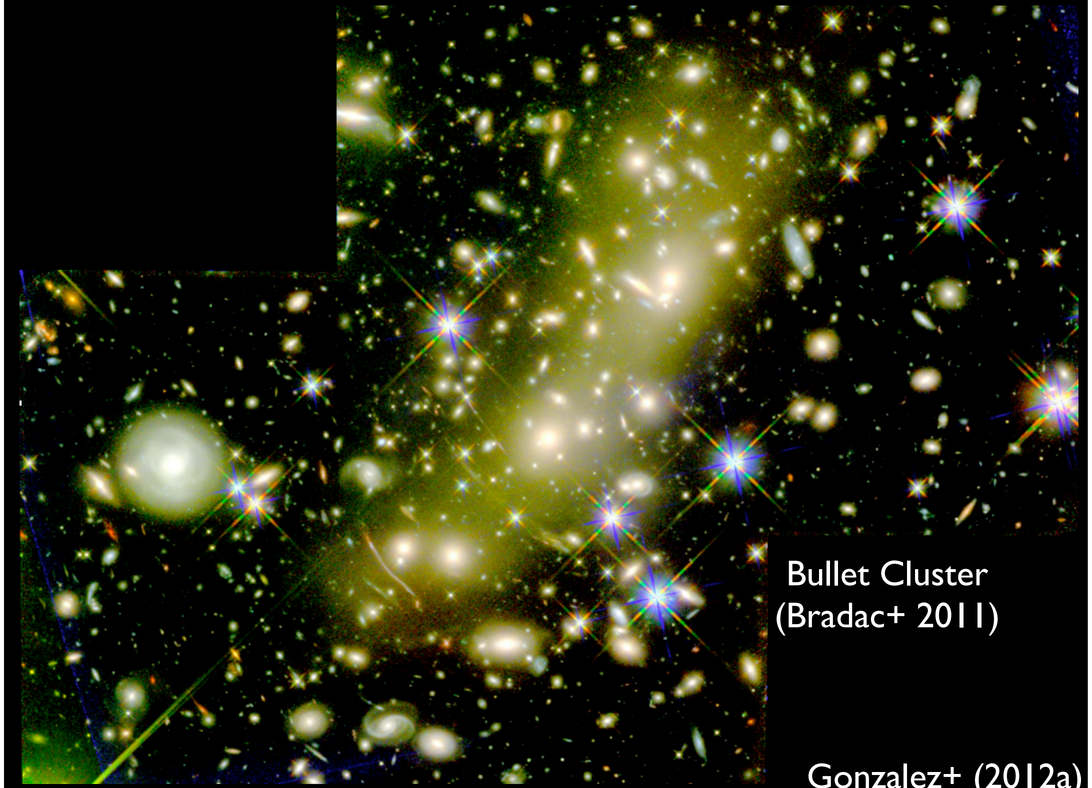
Sean Lake
Ned Wright
Alexey Vikhlinin
Casey Papovich
Matt Hilton
Dan Marrone
Yen-Ting Lin

Conor Mancone

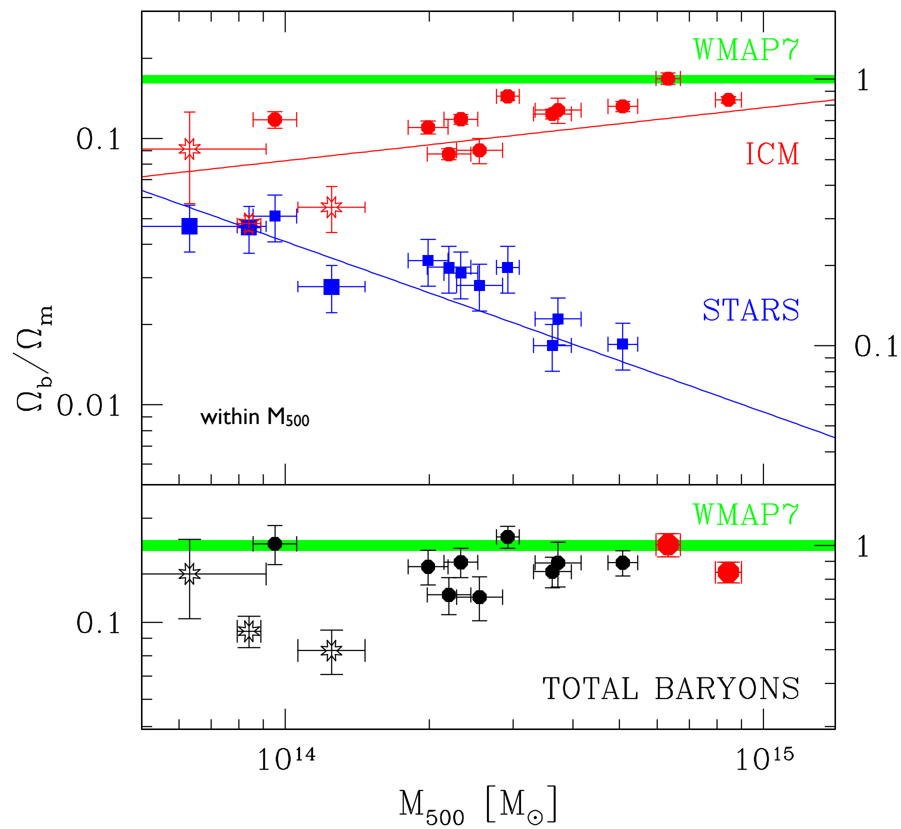
Galaxy Clusters: An Introduction

✔ Definitions and Basic Properties

- Working definition:
  - Galaxy cluster: A bound, collapsed structure with $M_{vir}>10^{14}\ M_\odot$
  - Galaxy group: A bound, collapsed structure with $M_{vir}<10^{14}\ M_\odot$ containing an association of galaxies
- Baryon fraction "close" to universal value
- Evolved stellar populations at z=0



Bullet Cluster
(Bradac+ 2011)

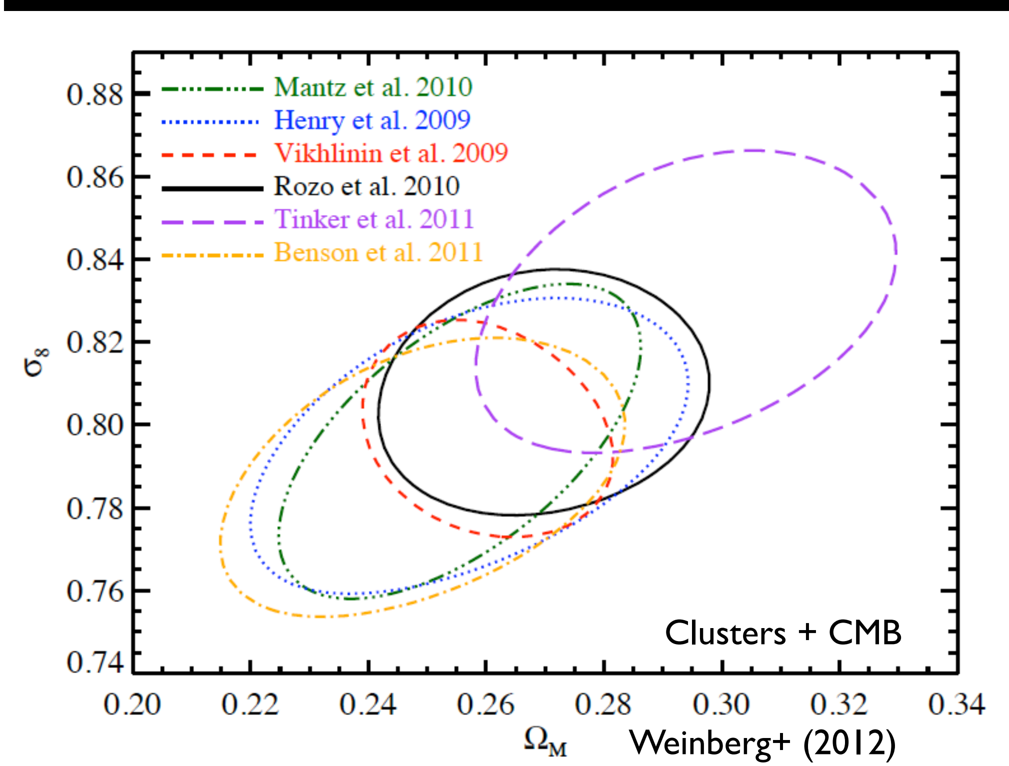


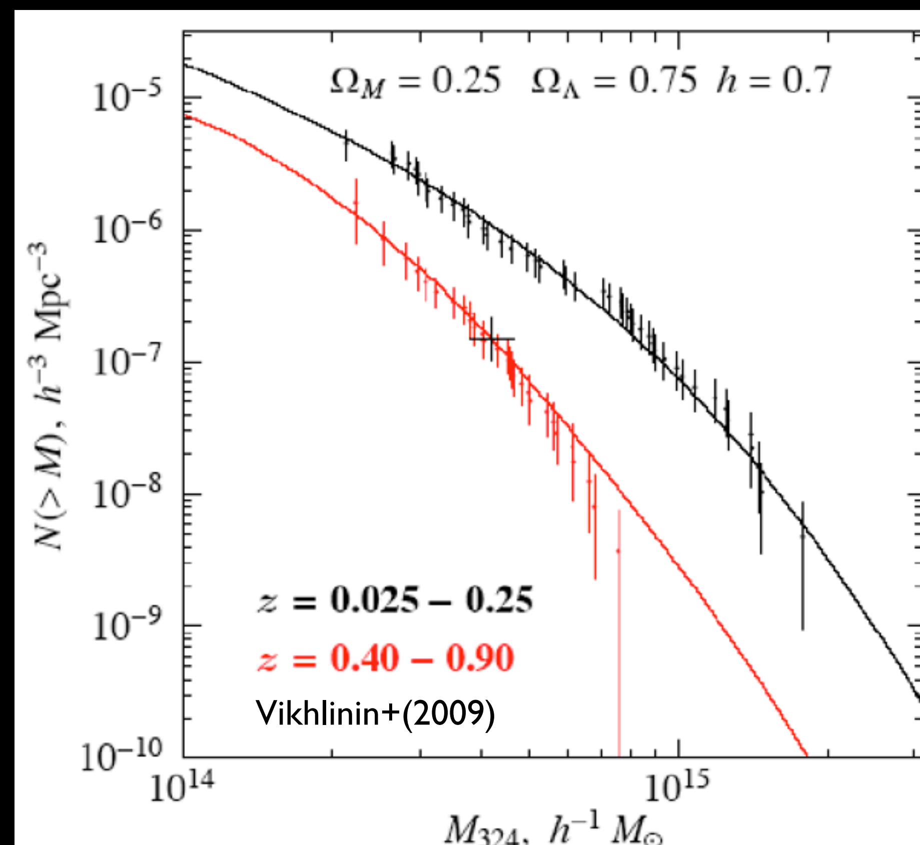
Gonzalez+ (2012a)

Applications: Cosmology

✔ **Galaxy Cluster Mass Function**

- **Normalization sensitive to parameter s_8**
- **Evolution of cluster mass function is a growth-of-structure test that depends sensitively on W_M and w**
- **Most extreme clusters at a given epoch provide test of primordial non-Gaussianity**





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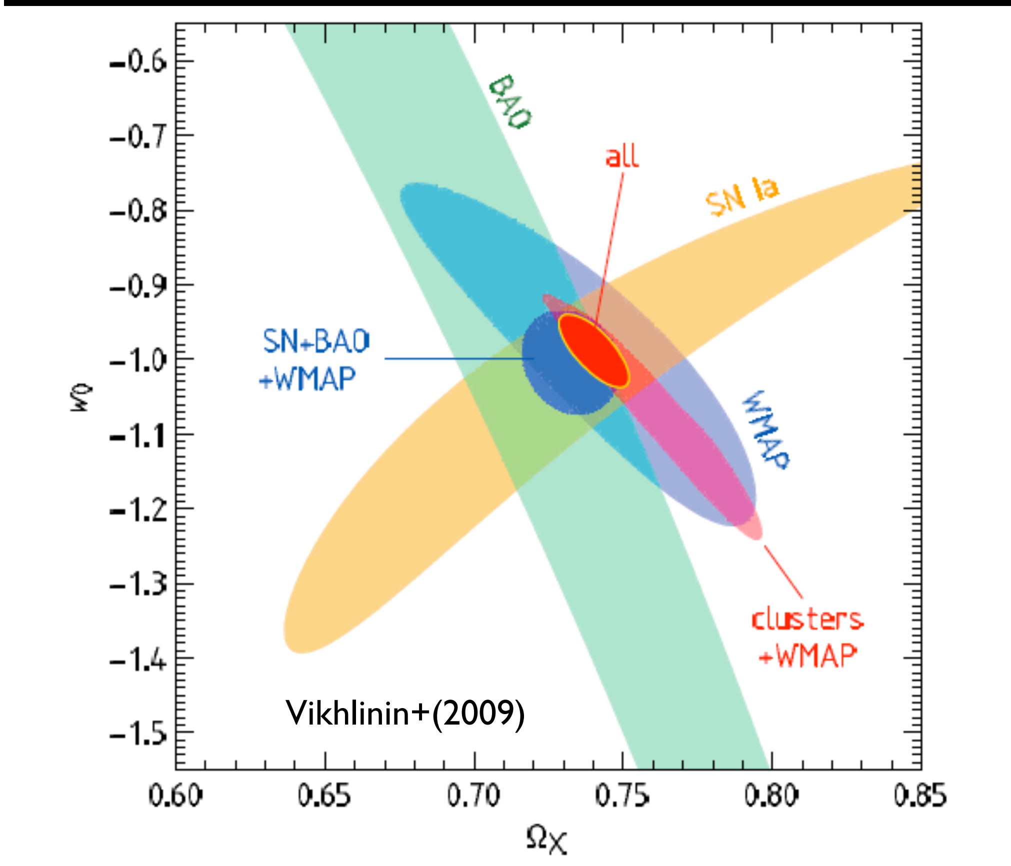
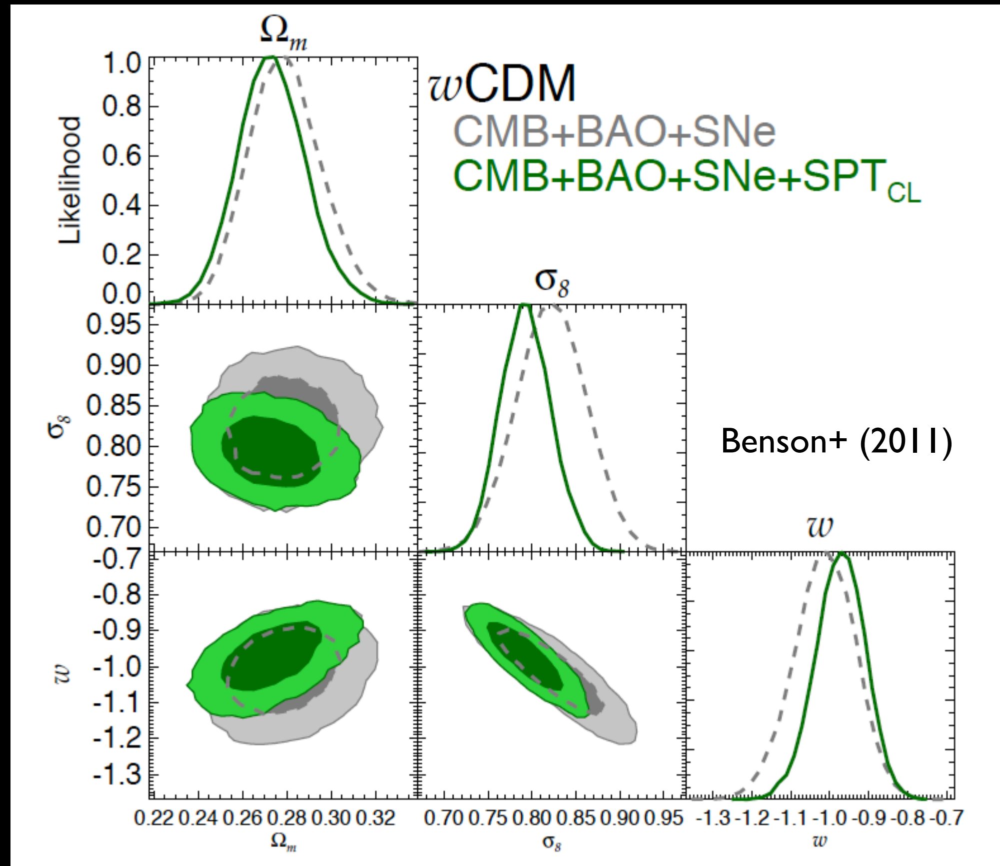
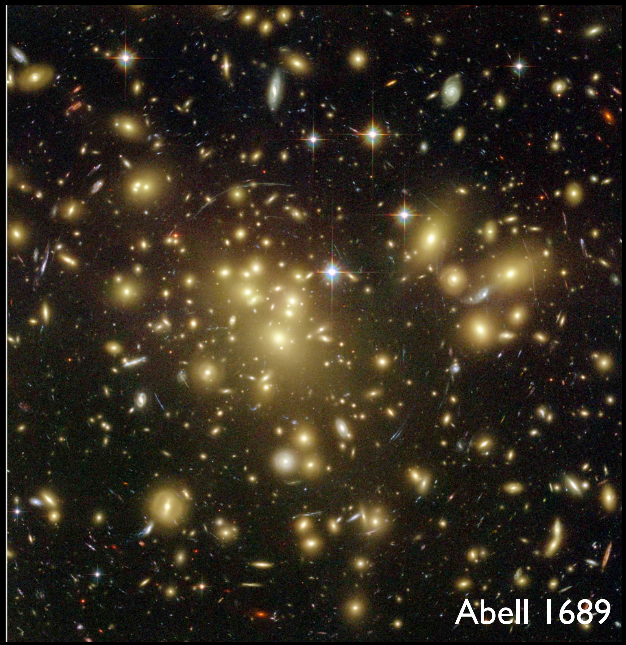




Applications: Galaxy Evolution



Clusters = Highest overdensity peaks, earliest structure formation

Efficient sites for studying:

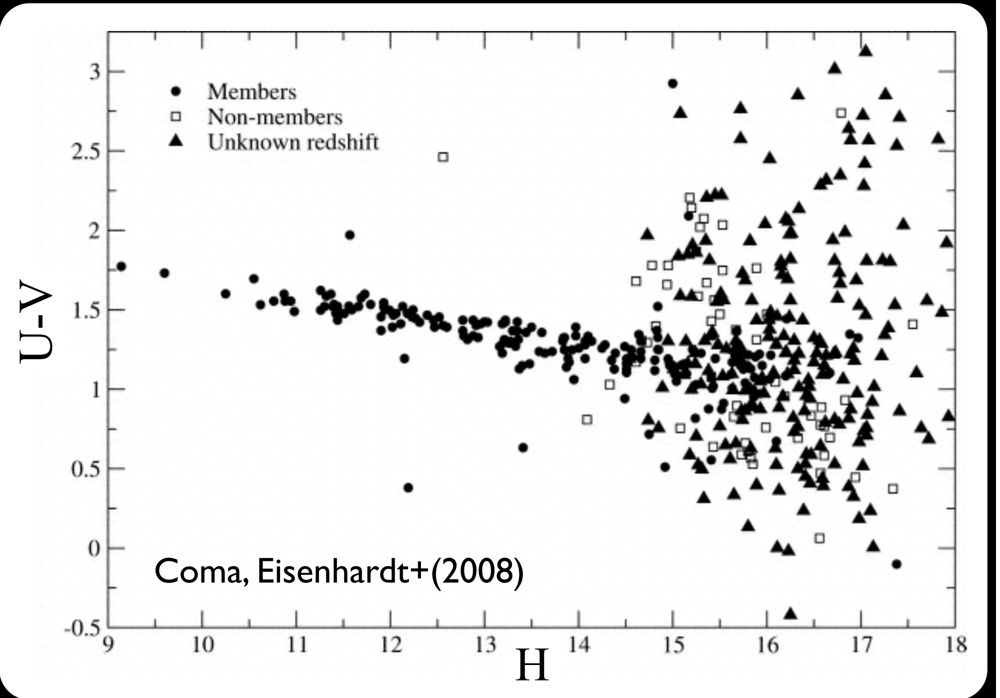
- ✔ Importance of environment in galaxy evolution
- ✔ Star formation and assembly histories of massive galaxies

Observables:

Evolution in

- Luminosity function
- Red sequence (color, scatter)
- Quiescent fraction
- Star formation rates
- Size

Minimal evolution observed at z<1 within cluster environment



High-Redshift Cluster Searches

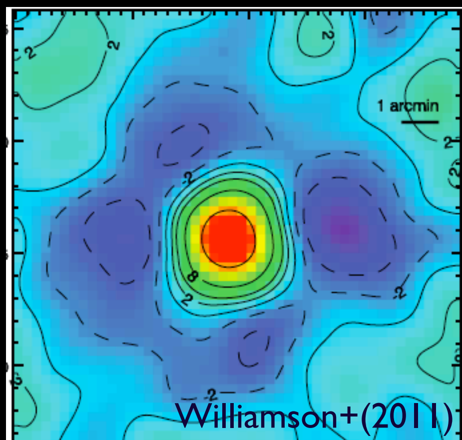
State of the Art

High-Redshift Cluster Searches

State of the Art

Sunyaev - Zel'dovich Effect

SPT, ACT, Planck



SPT-CL J2106-5844 at $z_{spec} = 1.133$.

Advantages:
- Wide area
- Unambiguous detections
- Immediate mass proxy
- Weak redshift dependence for mass limits

Challenges:
- Current mass limits relatively high

Status: Handful of massive ($M \sim 10^{15}\ M_\odot$) clusters published at $1<z<1.3$

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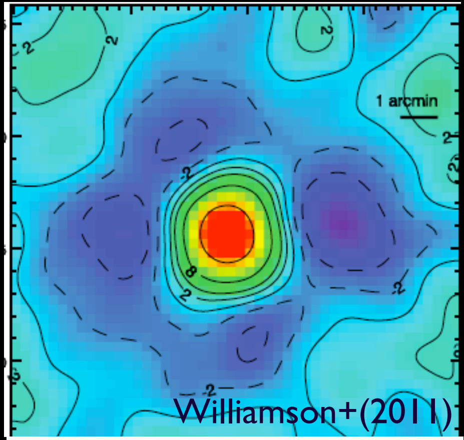

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X-ray

XMM (XCS, XDCP)

Advantages:
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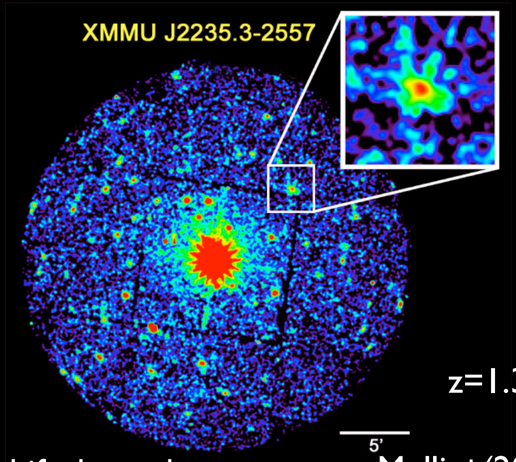
Challenges:
- Mass limits strongly redshift dependent
- AGN contamination - need optical/IR confirmation



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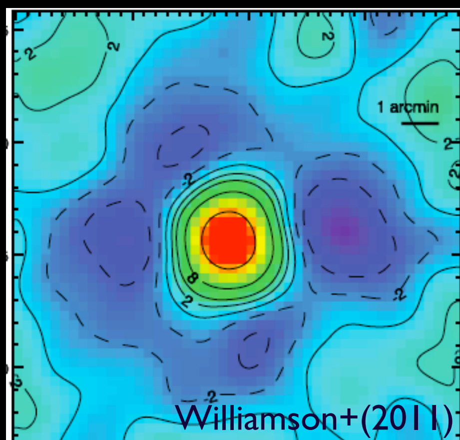

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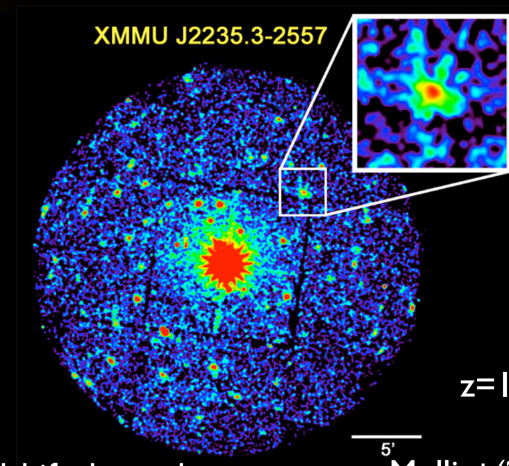

z=1.39

Mullis+(2005)

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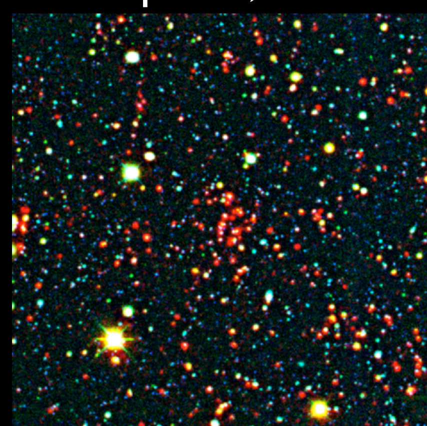
Galaxies

Spitzer, NIR *



Advantages:
- Sensitive down to low mass
- Weak redshift dependence for mass limits
- Greatest current redshift reach

Challenges:
- Projection effects
- Noisy mass proxy (**stellar mass**)

Status: Dozens of clusters and groups with $M \sim 5 \times 10^{13}$ - 5×10^{14} $M_\odot$ published at $1<z<2.2$

*And optical at z<1.2

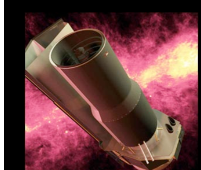
The IRAC Shallow Cluster Survey (ISCS)

The NOAO/Spitzer Deep Wide-Field (NDWFS/SDWFS)

- ✔ 9 deg^2
- ✔ Extensive Community Investment

NDWFS (B_WRI)
FLAMEX (JK_s)
IBIS (JHK_s)

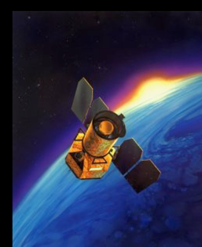
IRAC Shallow Cluster Survey



IRAC Shallow Survey
MAGES (MIPS)
Spitzer Deep Wide-Field Survey

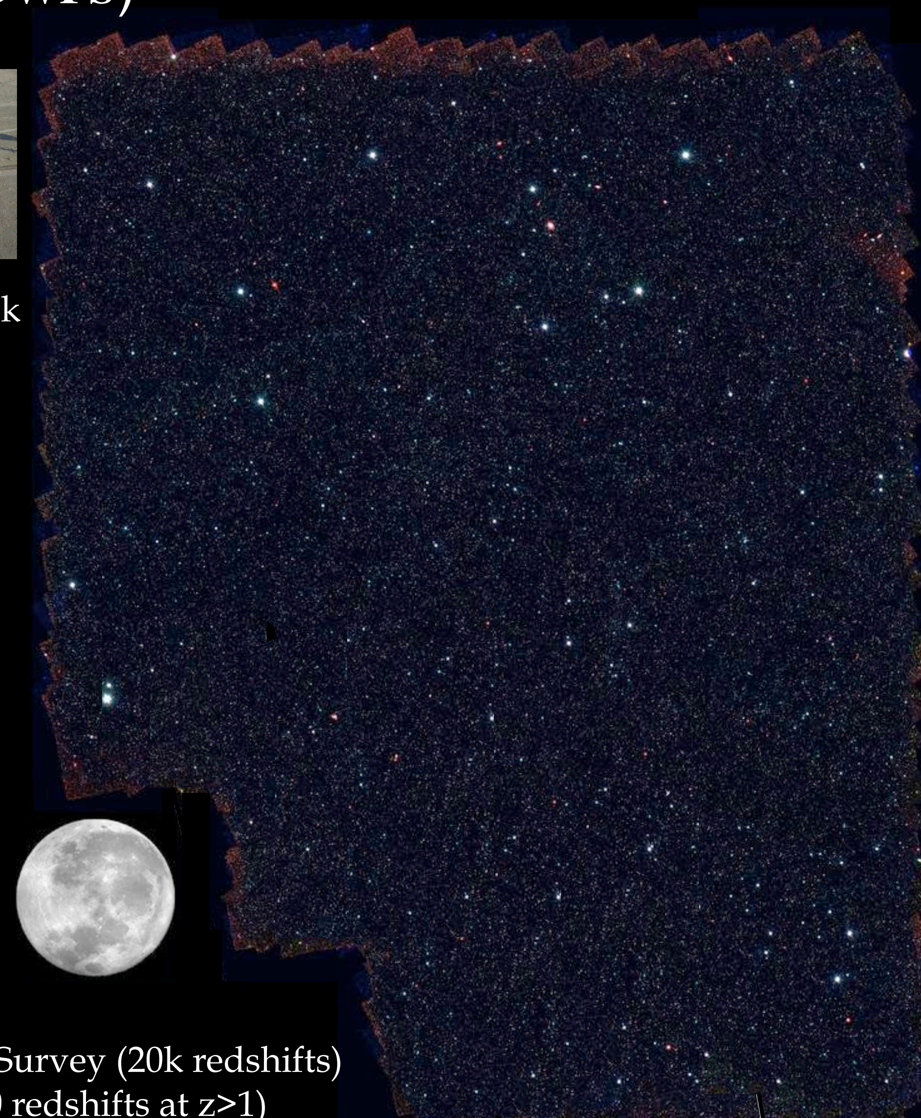
Chandra XBootes Survey

VLA & Westerbork



GALEX

Herschel GTO



AGES Spectroscopic Survey (20k redshifts)
Keck & Gemini (>400 redshifts at z>1)

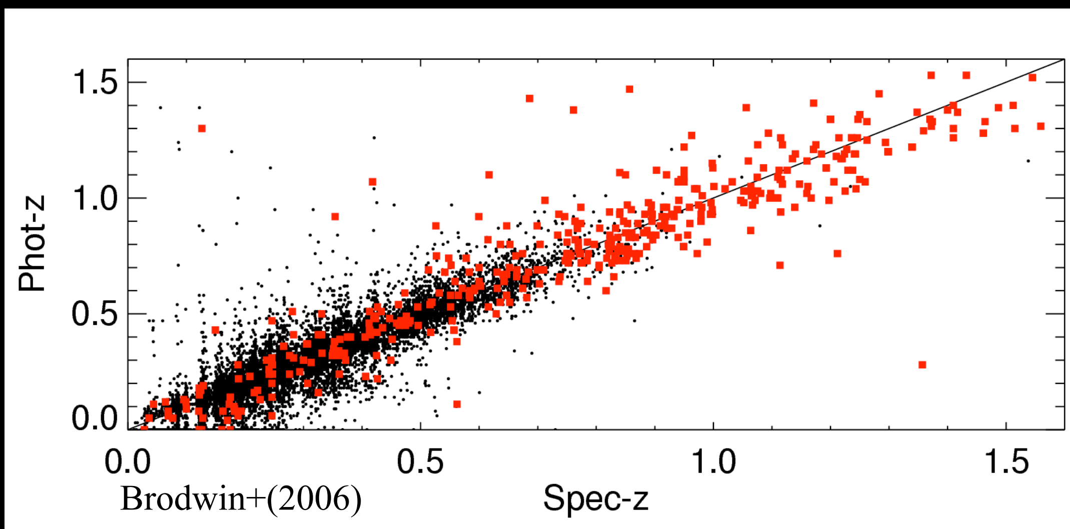
The IRAC Shallow Cluster Survey (ISCS)

Key Ingredients

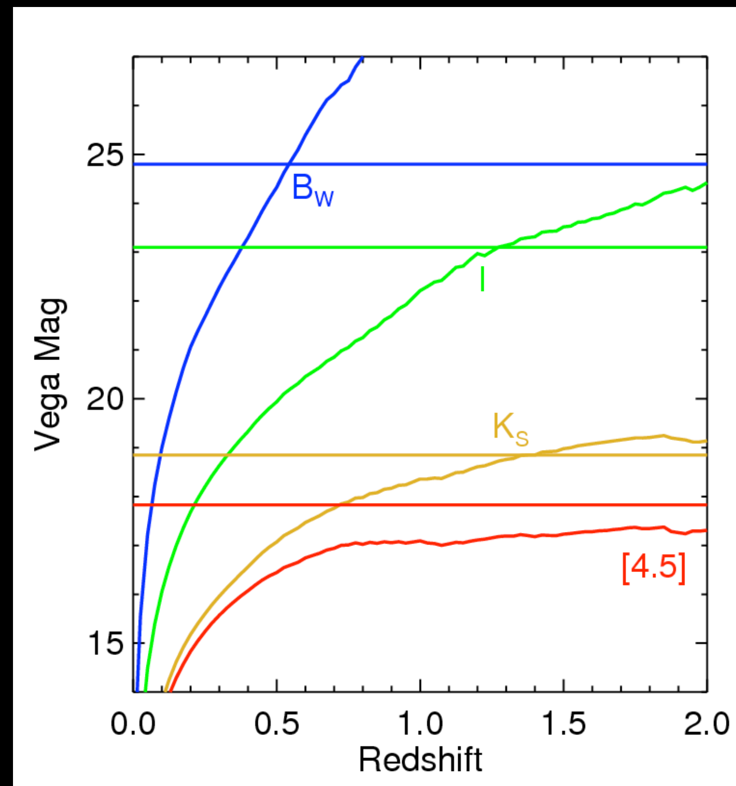
✔ 4.5 µm galaxy selection

✔ Photometric redshifts with full redshift probability distribution, for every galaxy

✔ Wavelet detection algorithm



$s_z/(1+z) = 0.059$ $s_{blue} \approx s_{red}$



4.5 µm selection yields nearly constant stellar mass limit at z≥0.7

Stanford+ (2005), Elston+ (2006), Eisenhardt+(2008)

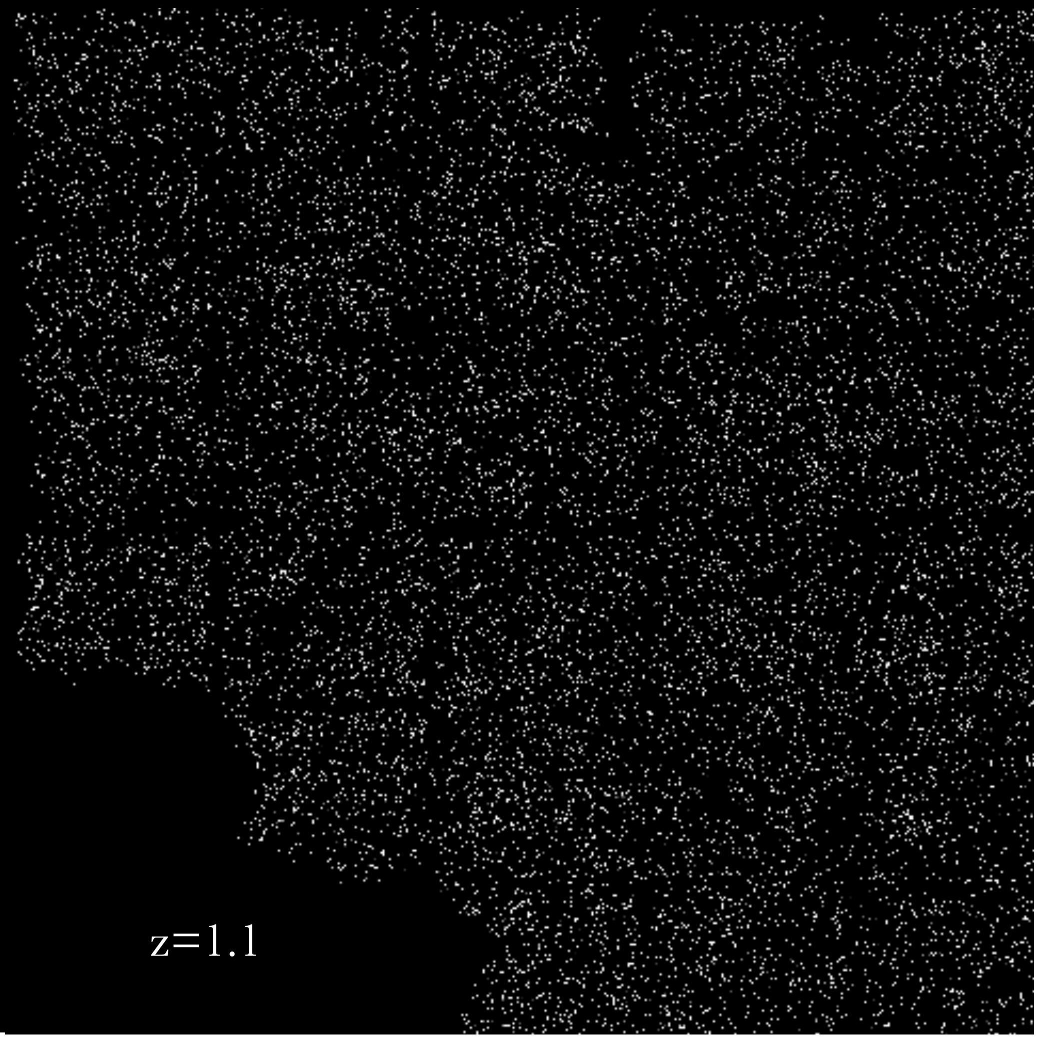
The IRAC Shallow Cluster Survey (ISCS)

Detection Method

✔ P(z) ⇒ Redshift sliced density maps (Δz=0.2, z=0.1-2)

✔ **Convolve with a wavelet kernel of fixed physical scale**

✔ **Merge detections from overlapping redshift slices**



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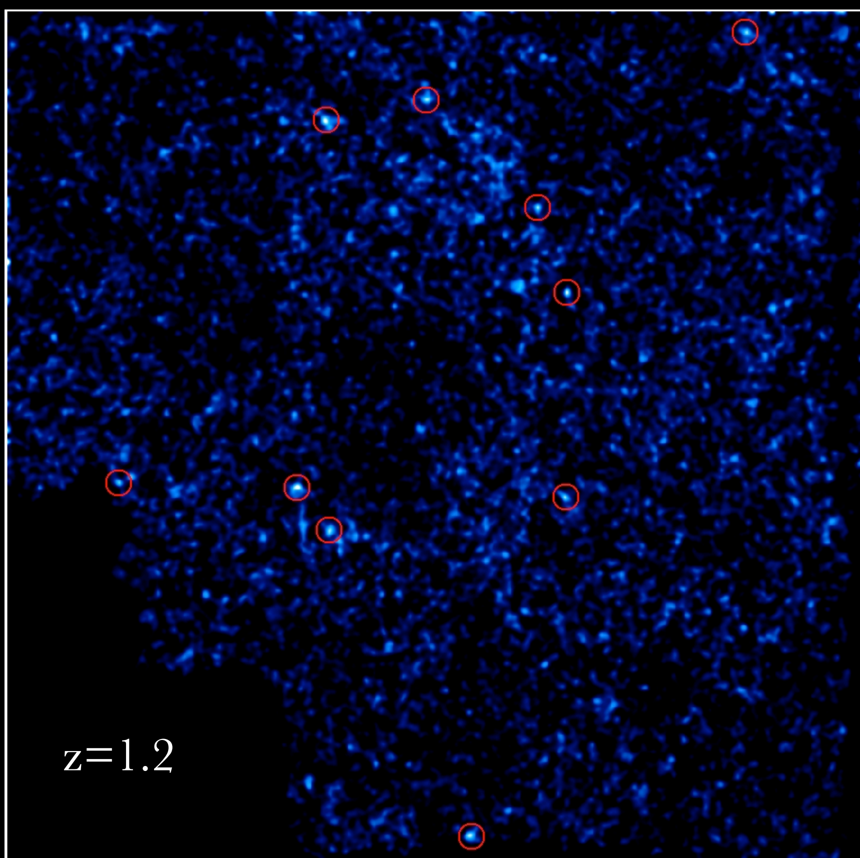
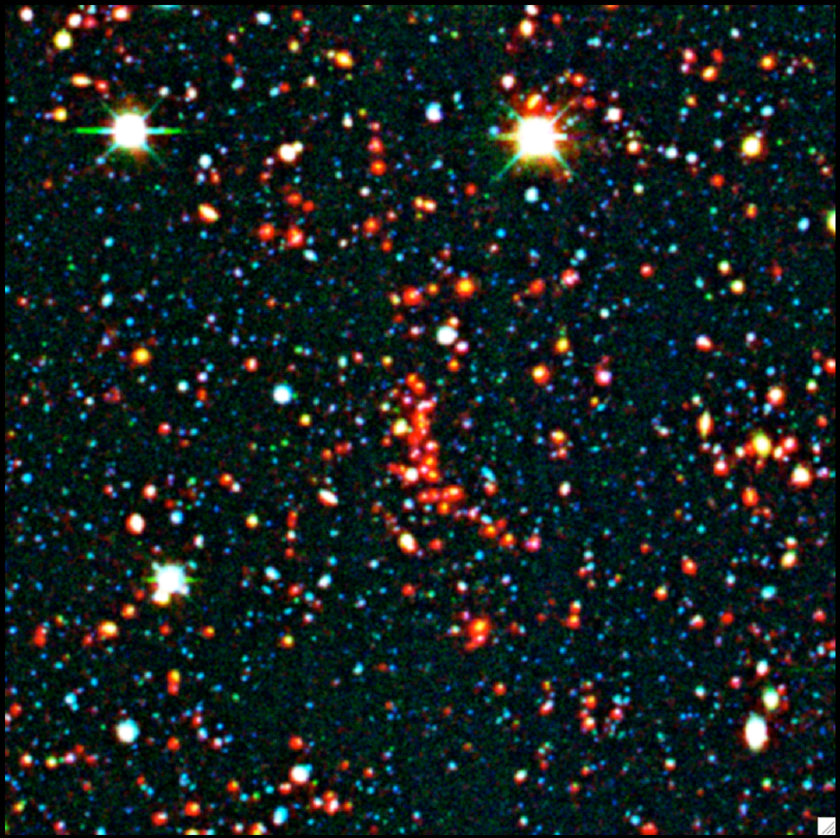


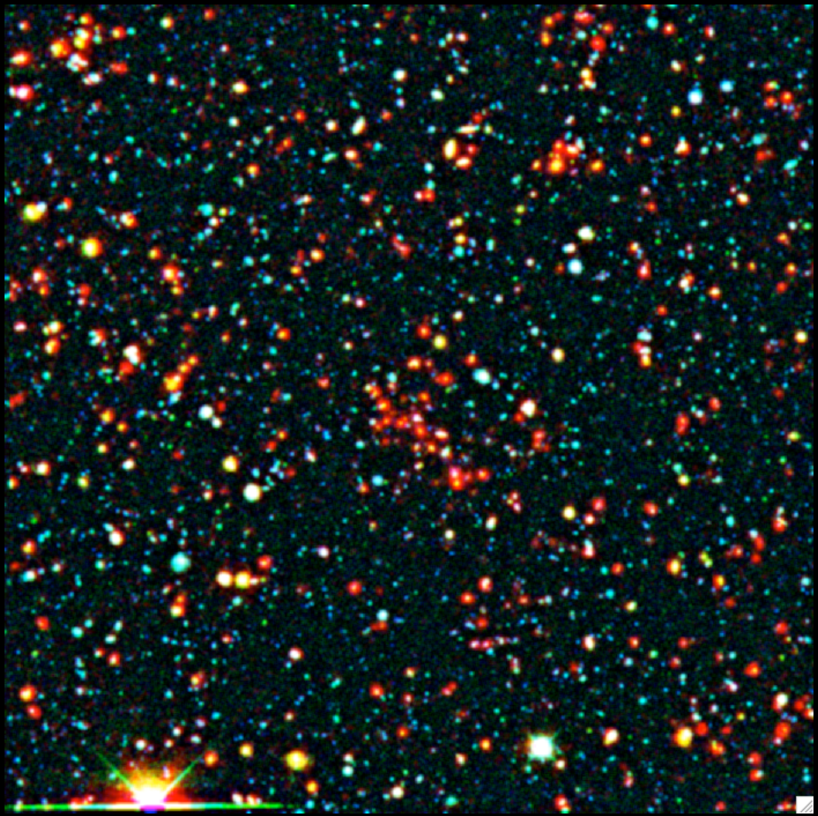
Examples from the ISCS Rogues Gallery

$B_W RI$

Examples from the ISCS Rogues Gallery



<z> = 1.243



<z> = 1.487

$B_wI[4.5]$

The IRAC Shallow Cluster Survey

Ensemble Properties

✔ Large cluster/group sample spanning wide redshift range

- 100+ clusters and groups at z>1
- <10% false detections at z>1

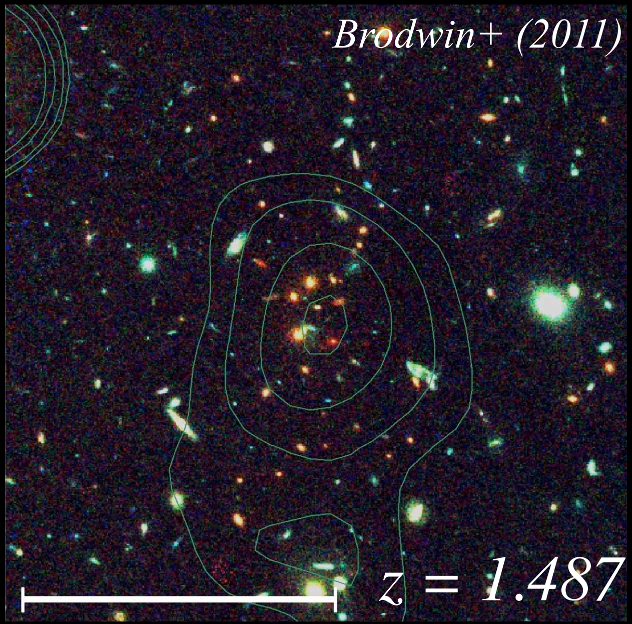
✔ High fidelity photometric redshifts for all candidates

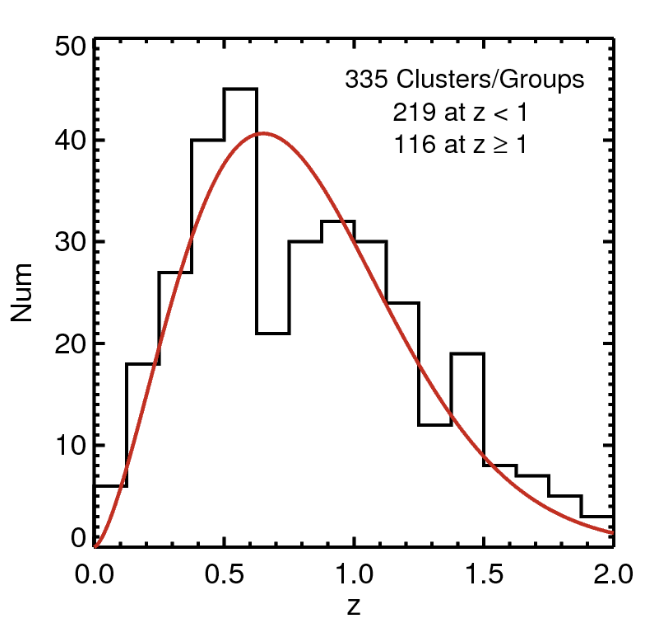
- ~20 spectroscopically confirmed from ISCS at 1<z<1.5

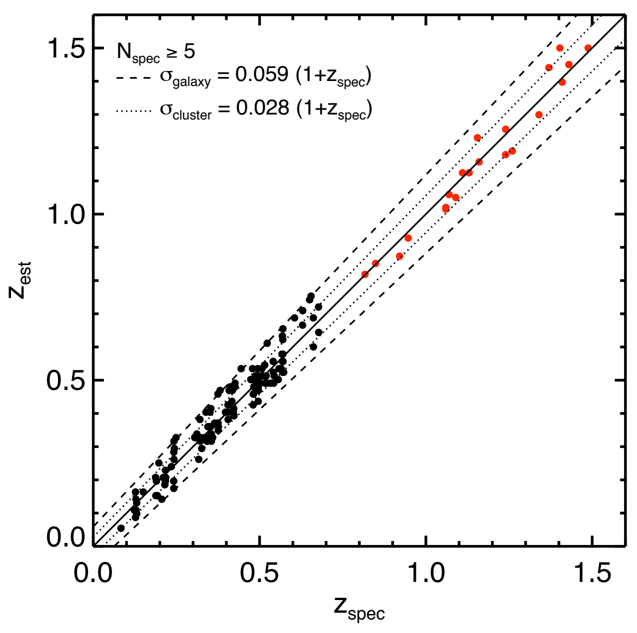
✔ Highest significance detections are massive clusters

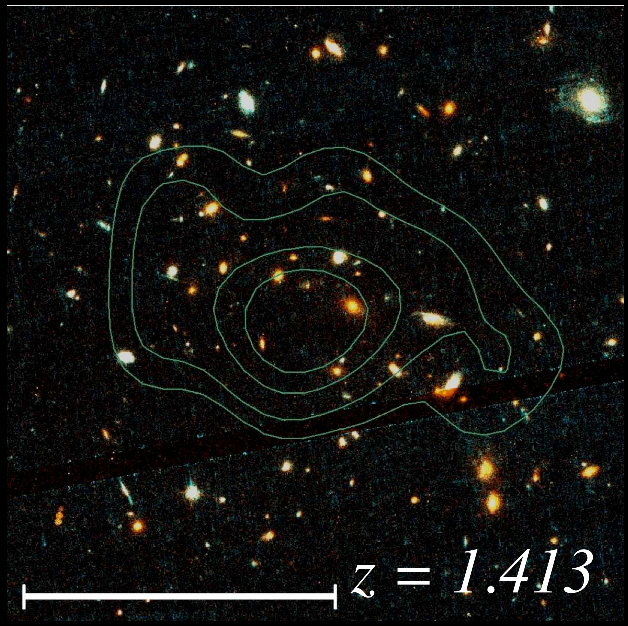
✔ Roughly constant mass threshold at 0.7<z<1.5

- $M_{200} \gtrsim 5 \times 10^{13}\ M_{\odot}$









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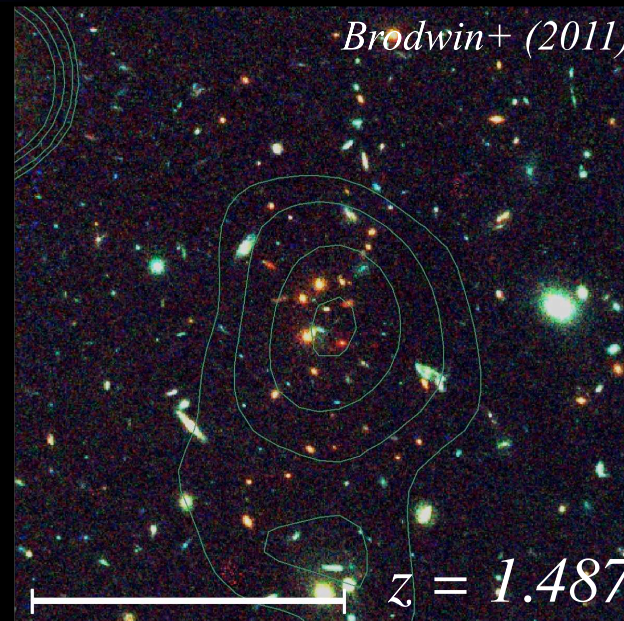

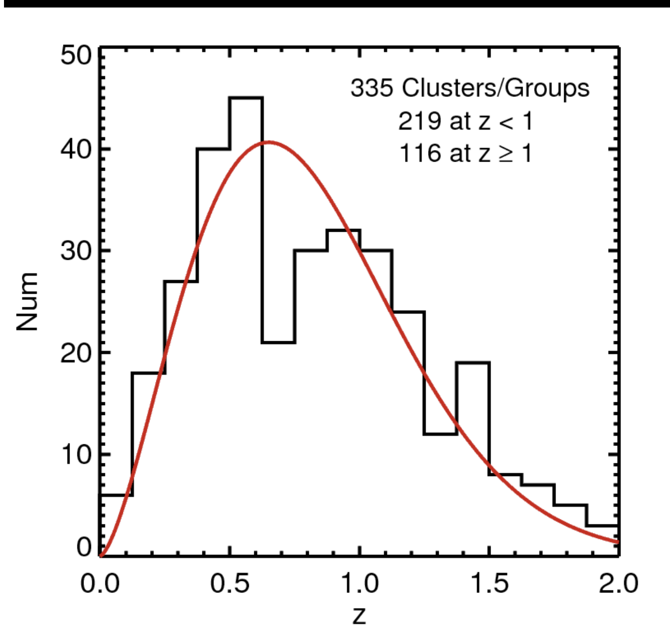

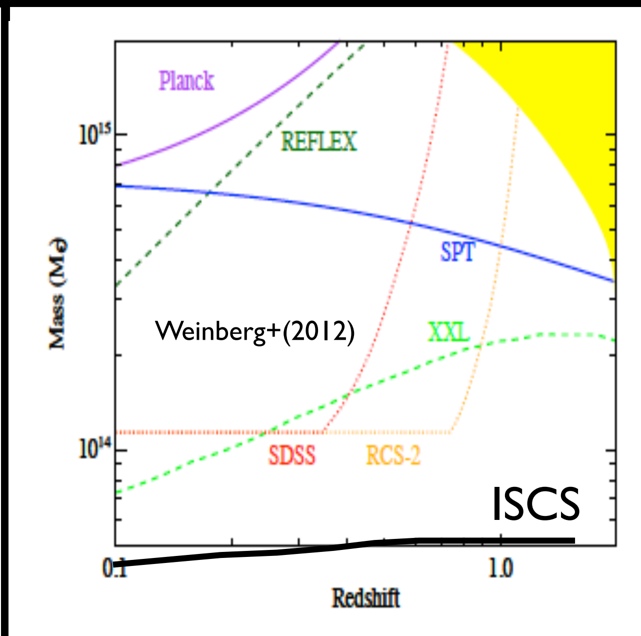

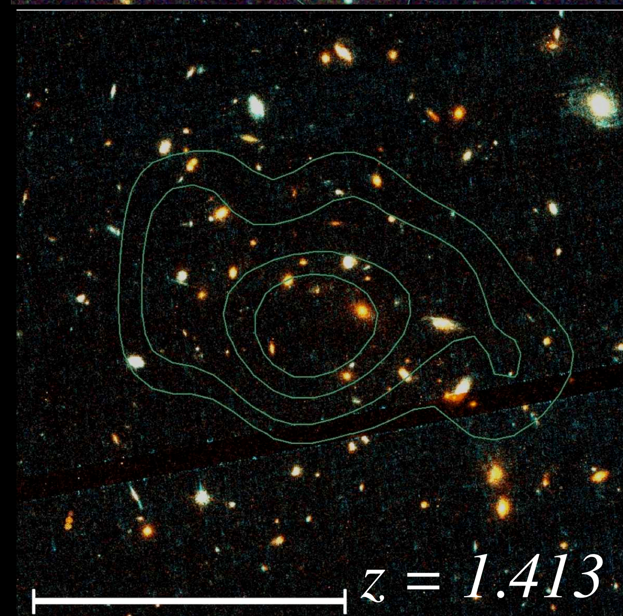

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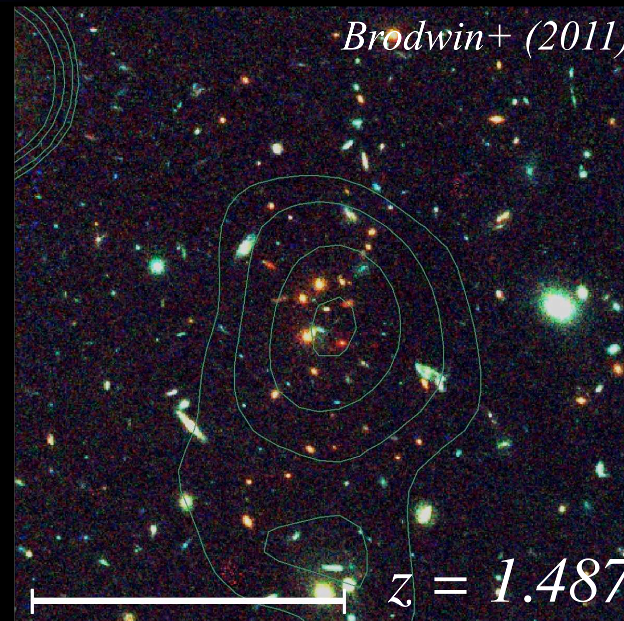
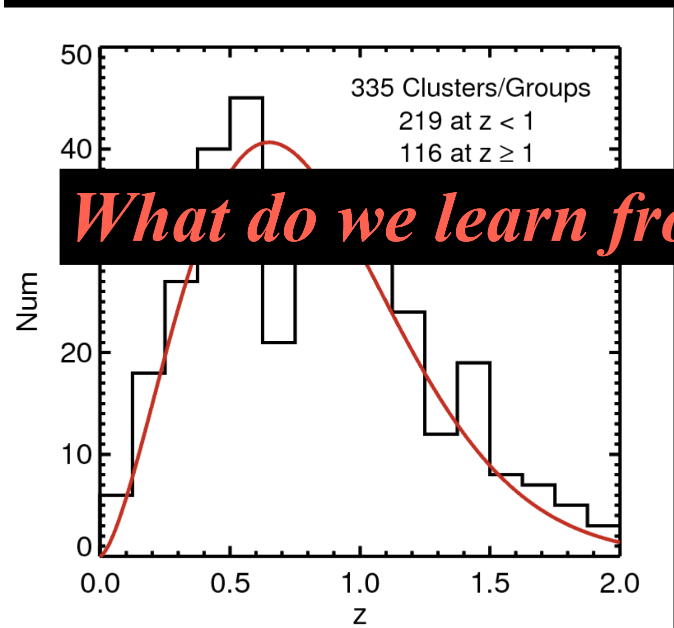
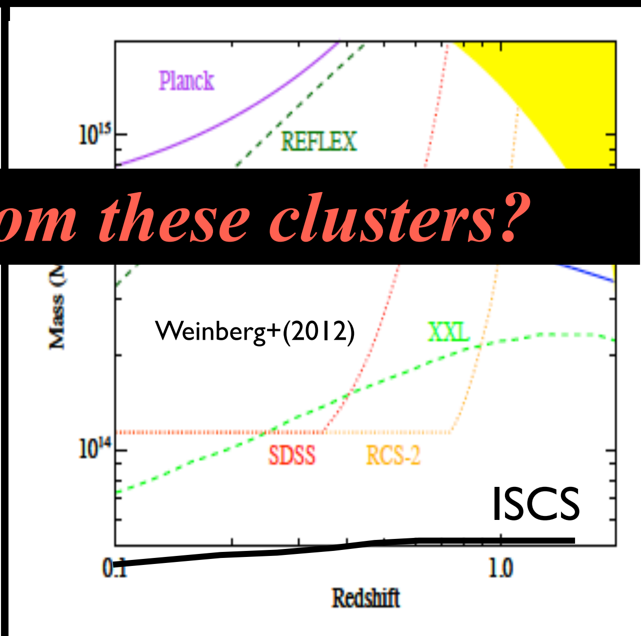
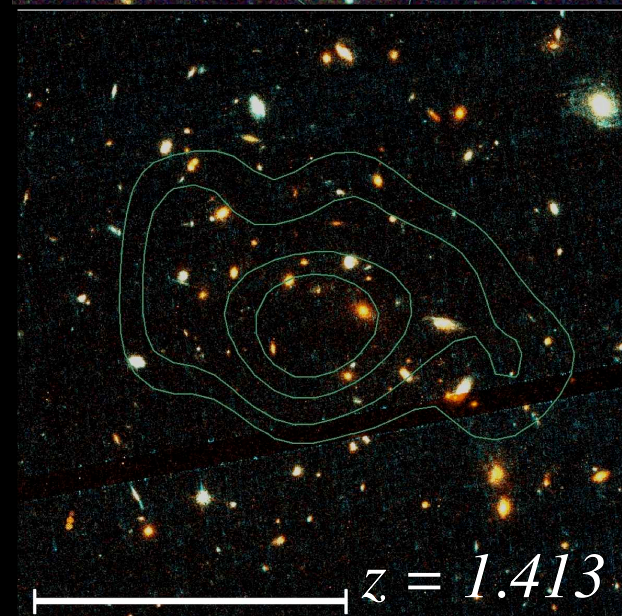


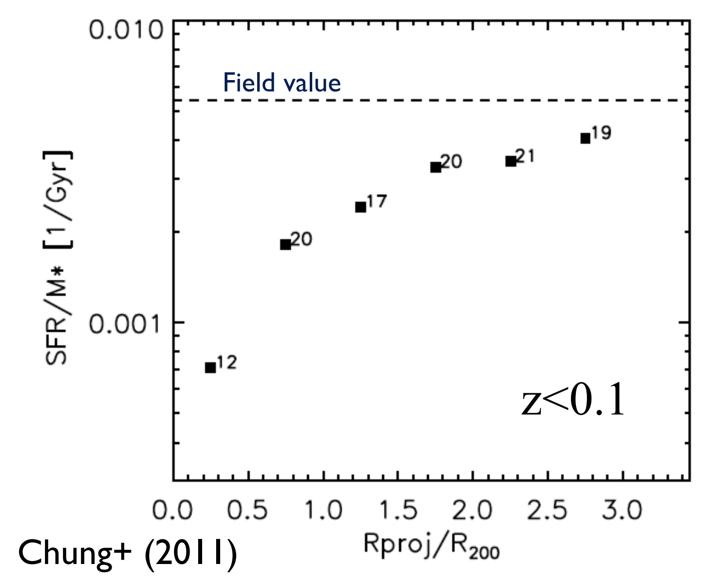


What do we learn from these clusters?





Star Formation in Clusters

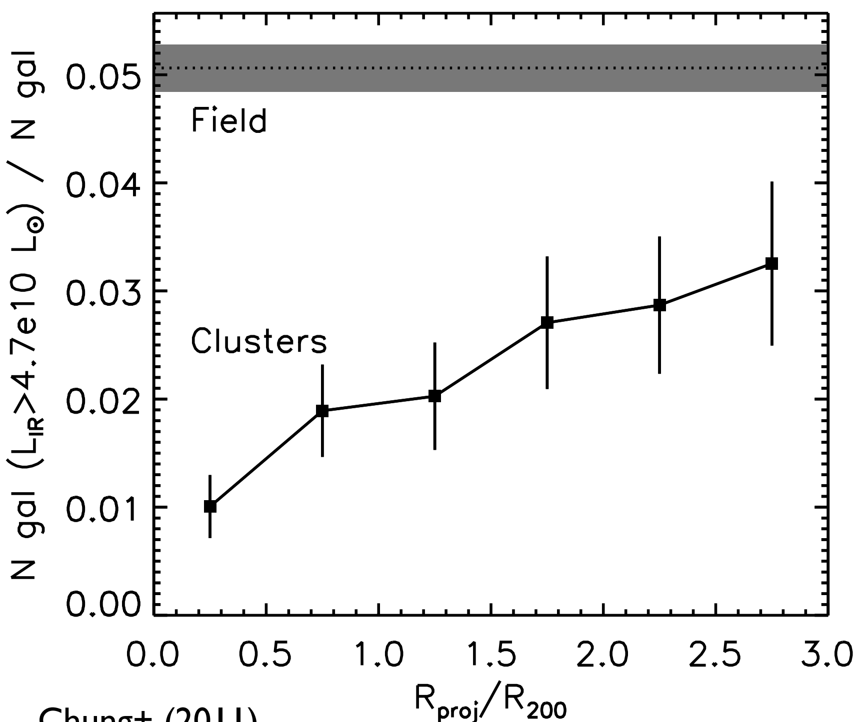


Chung+ (2011)

Direct observations of star formation

At z<1

- Star formation depressed in clusters relative to field
- Star formation rate decreases towards center



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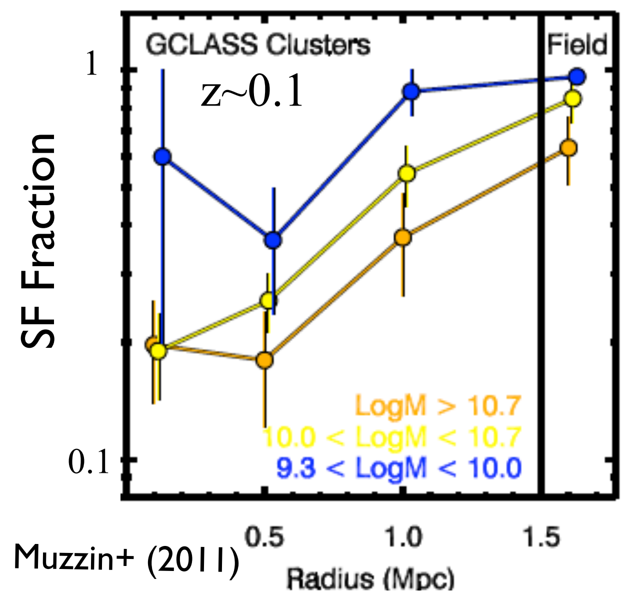
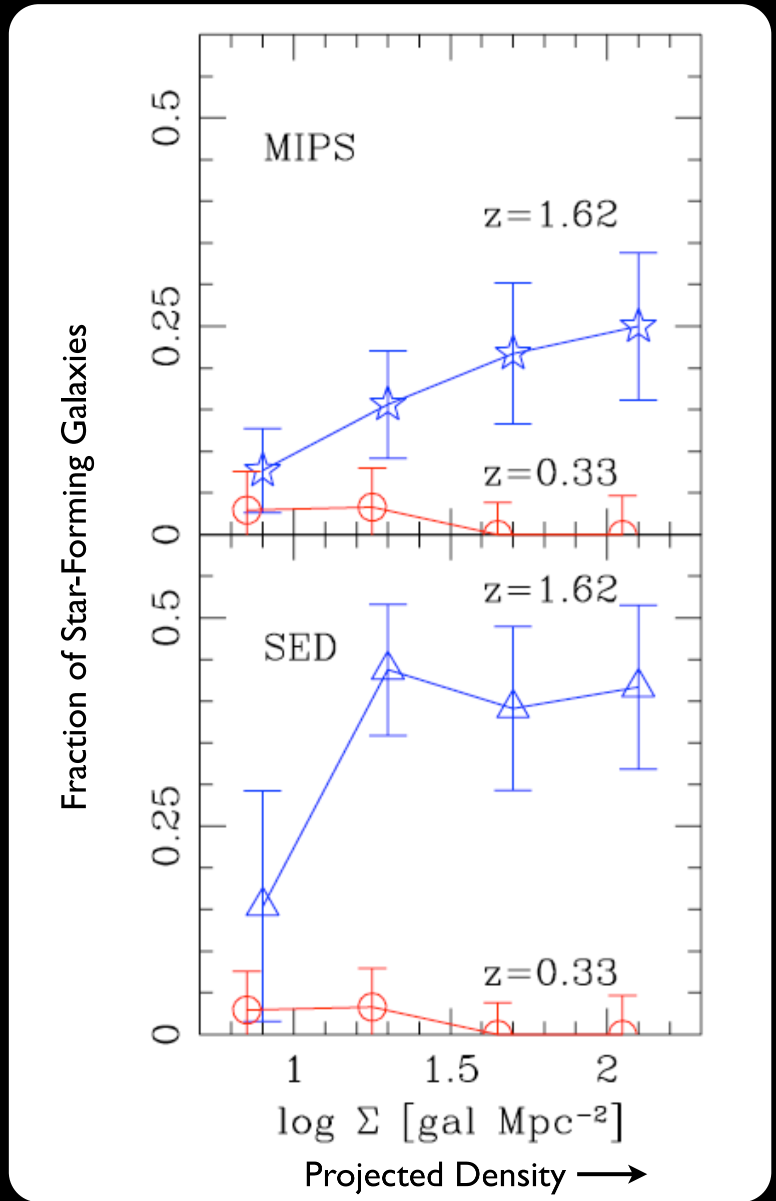


Muzzin+ (2011)

Star Formation in Clusters

- SF fraction increases toward core/higher density
  - Seen by several groups for individual clusters
    - Hilton+(2010), Tran+(2011)
- Increasing amplitude with redshift



Tran+ (2011)

Our sample:

- 18 clusters at 1<z<1.5 with deep MIPS data
- Cluster detection independent of presence of red sequence

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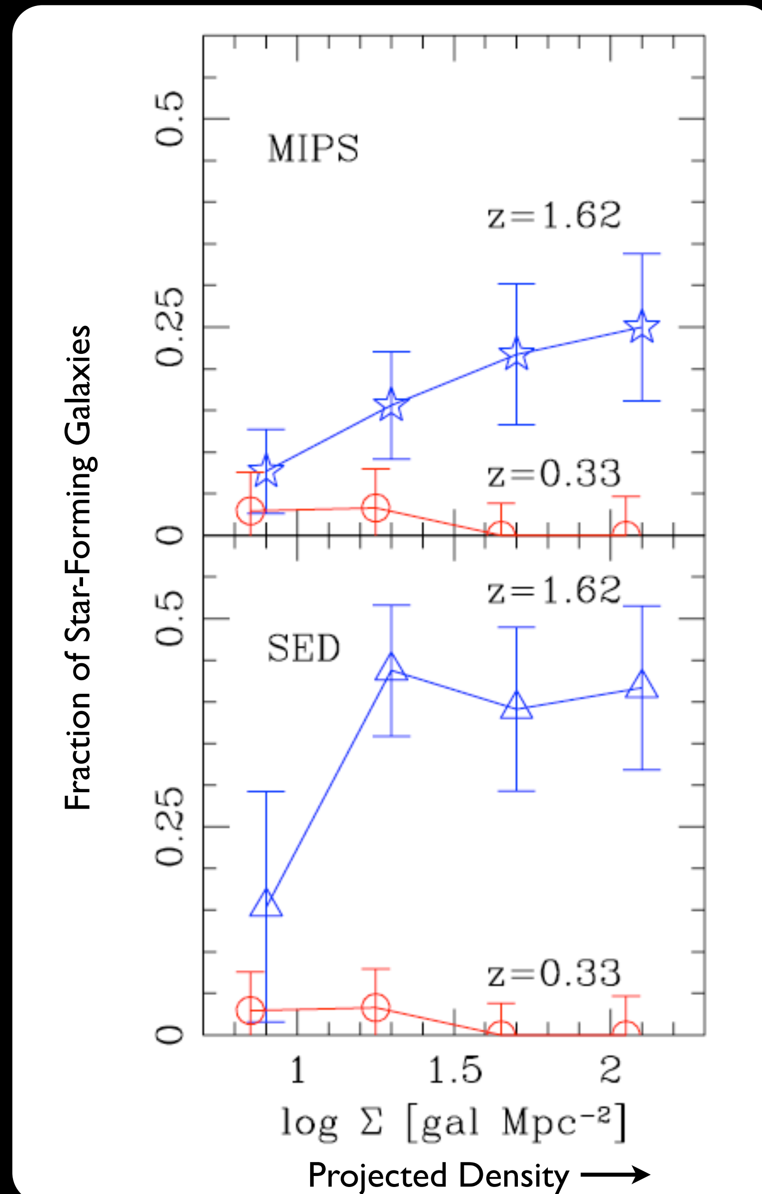

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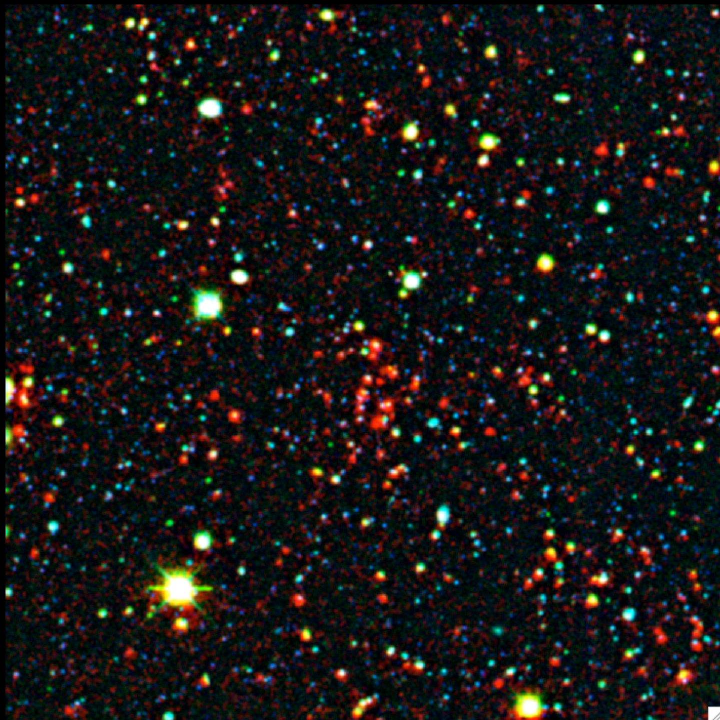
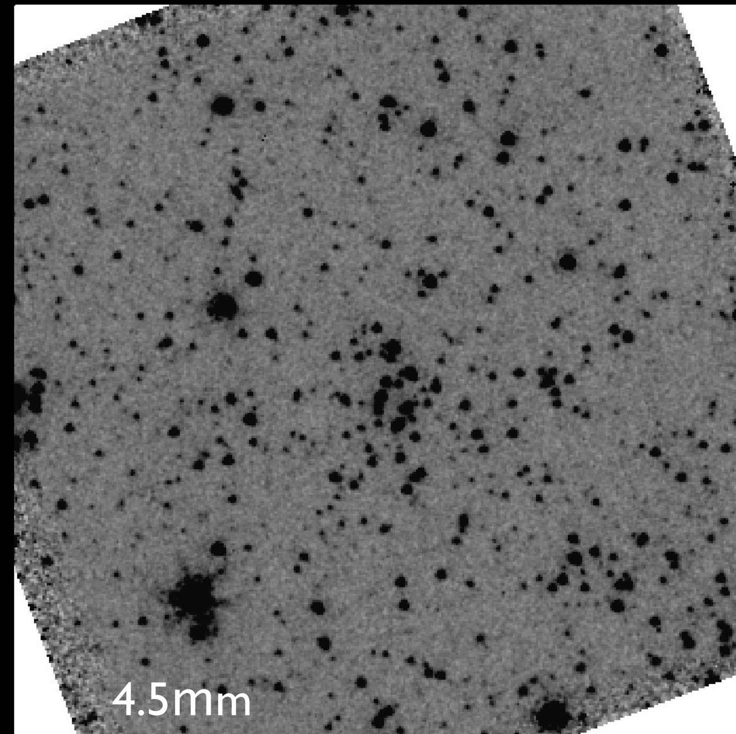
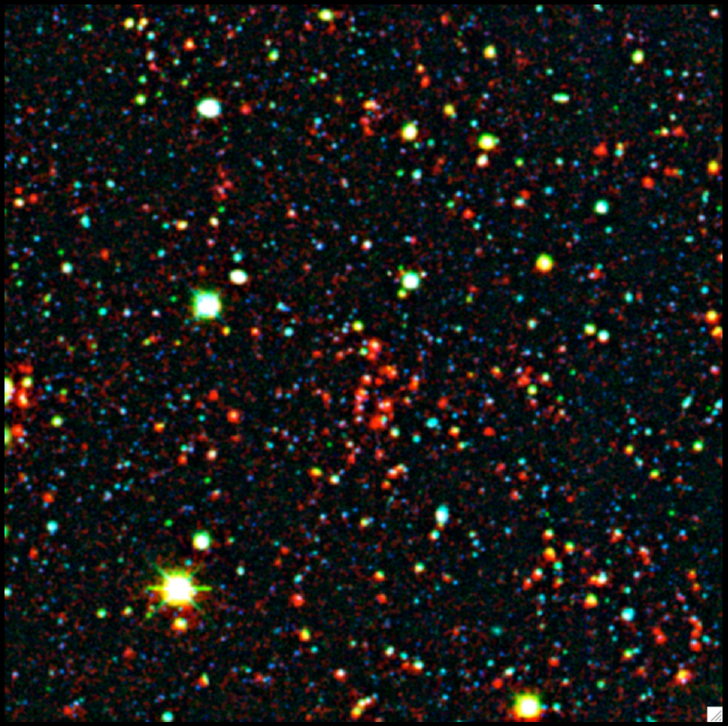
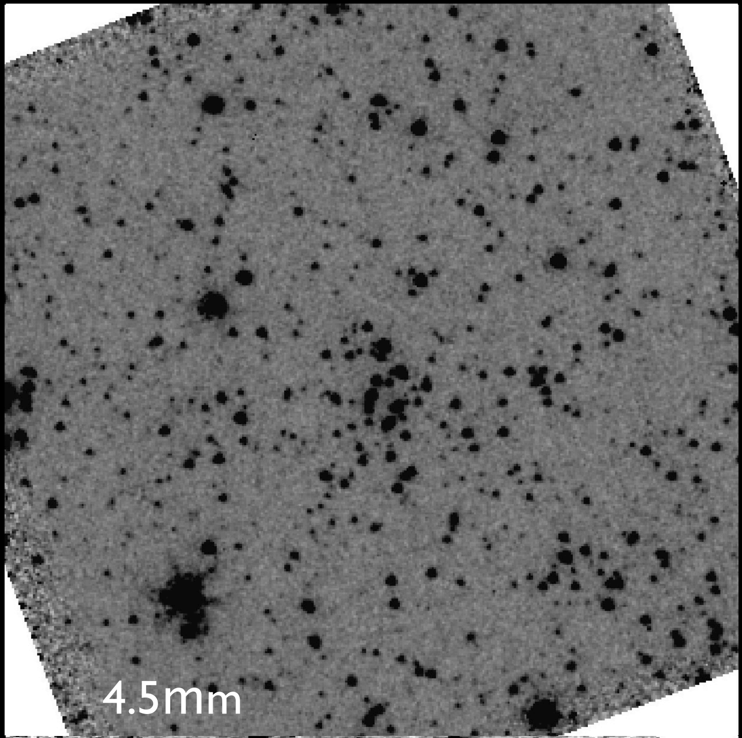


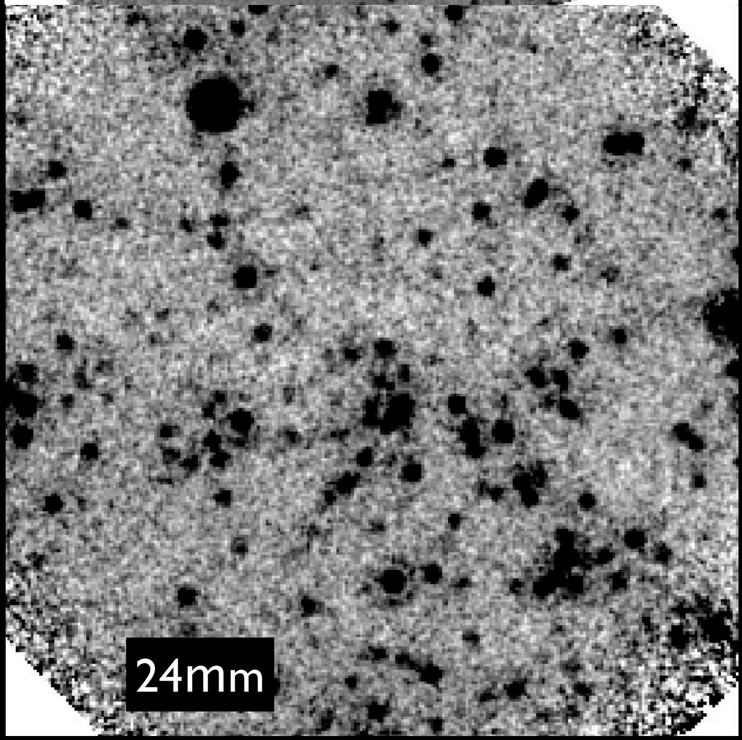
z=1.37



Brodwin+ (2012b, in prep)







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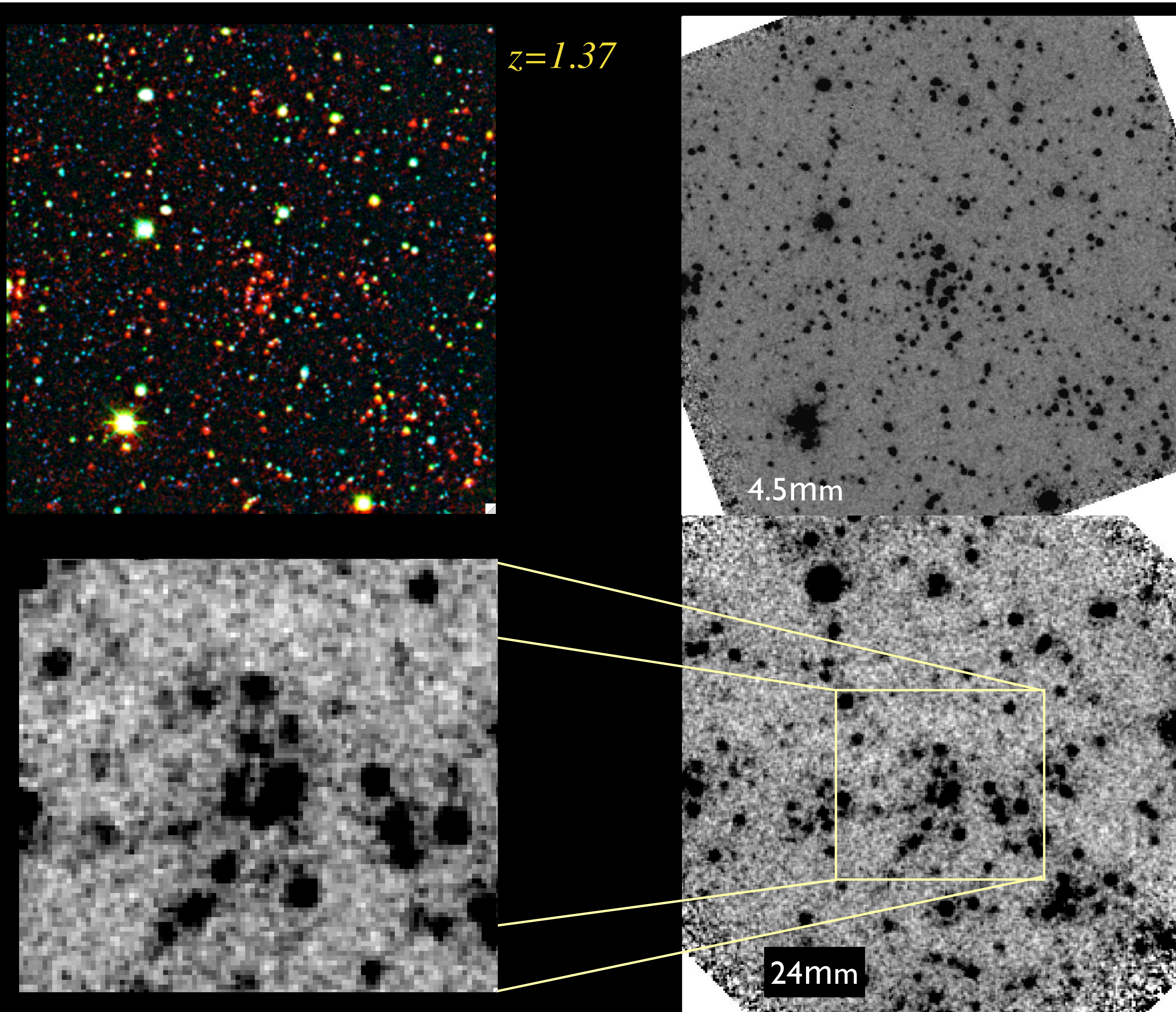

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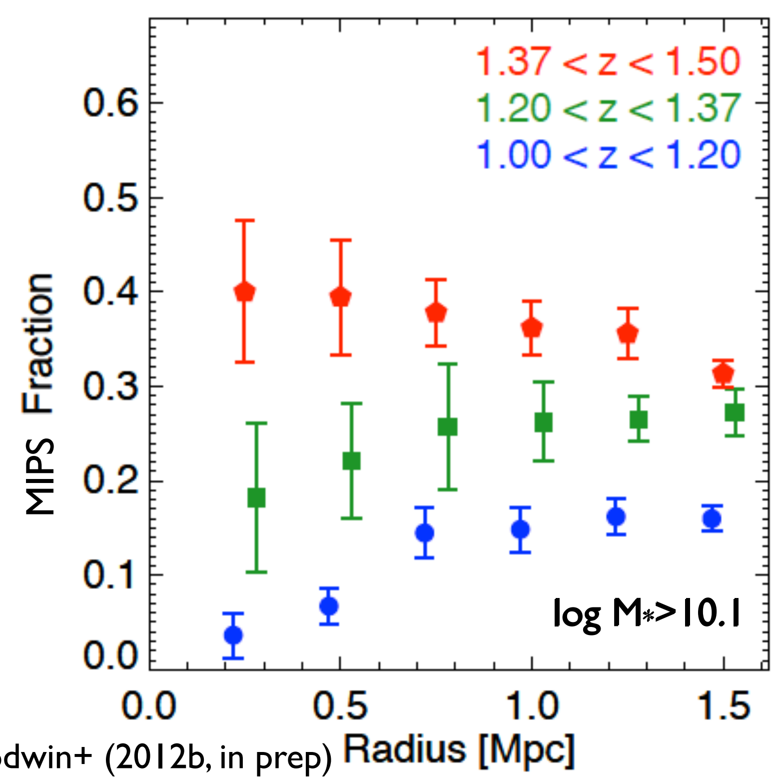

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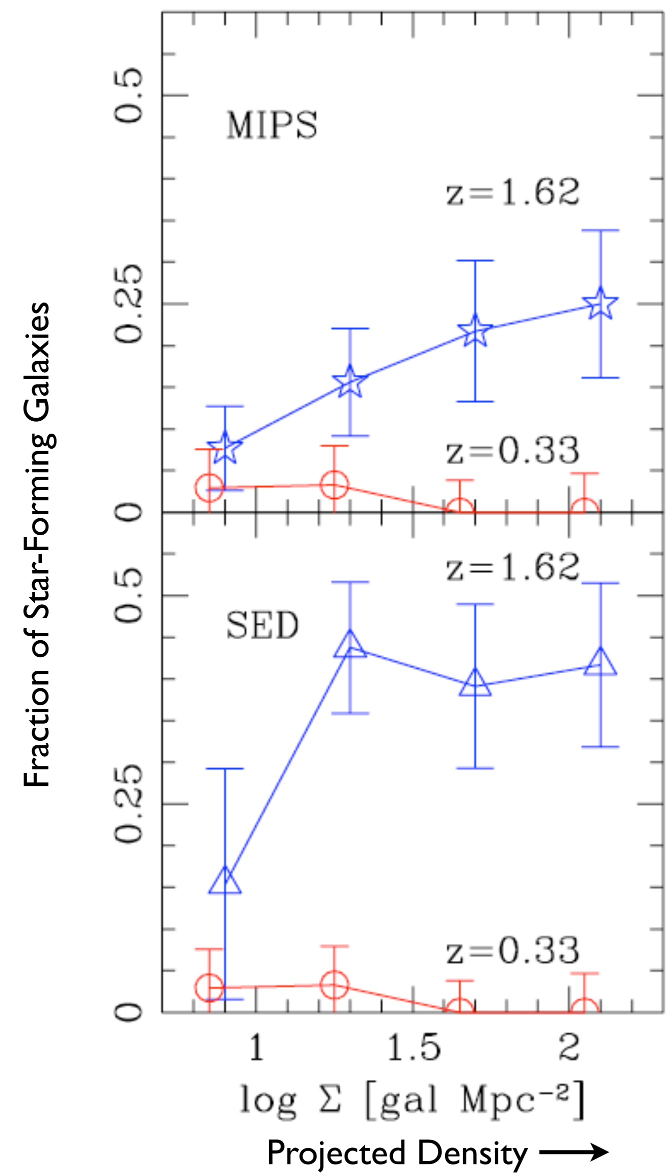


Tran+ (2011)

Evolution of the Red Sequence

Detailed observations of individual clusters enable interesting constraints.

Sample

- 18 Clusters at $1<z<1.5$
- F814W+F160W imaging of core regions
- HST/WFC3 grism + Keck spectroscopy

Key Observables

- Color Evolution
- Scatter in Red Sequence colors

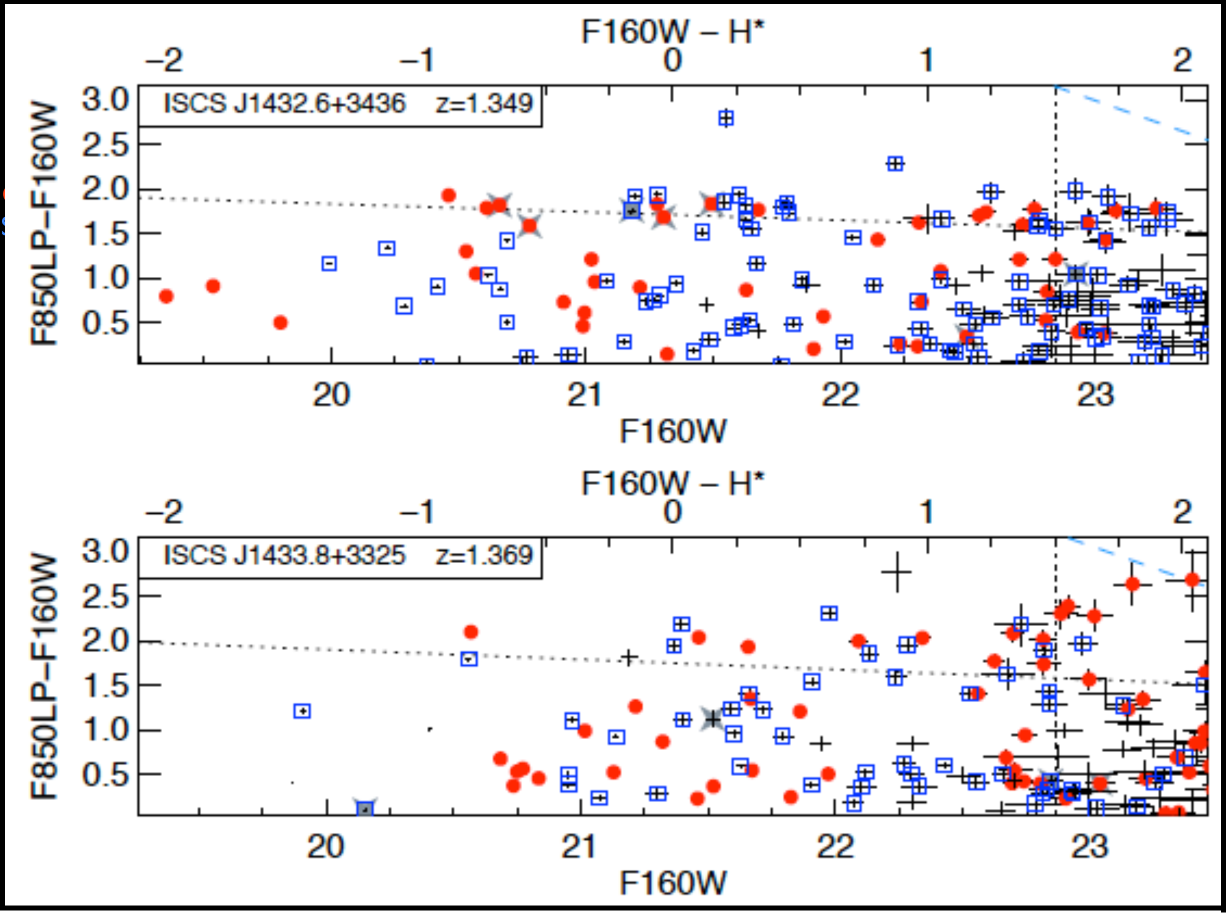
Red sequence selection:

- $H<H^*+1.5$
- Early type ($n>2.5$)

Mean and total scatter computed using biweight estimator

Photometric scatter computed via bootstraps

□ = color offset relative to evolved Coma model for $z_f=3$



Snyder+ (2012)

Evolution of the Red Sequence

Detailed observations of individual clusters enable interesting constraints.

Sample

- 18 Clusters at 1<z<1.5
- F814W+F160W imaging of core regions
- HST/WFC3 grism + Keck spectroscopy

Key Observables

- Color Evolution
- Scatter in Red Sequence colors

Red sequence selection:

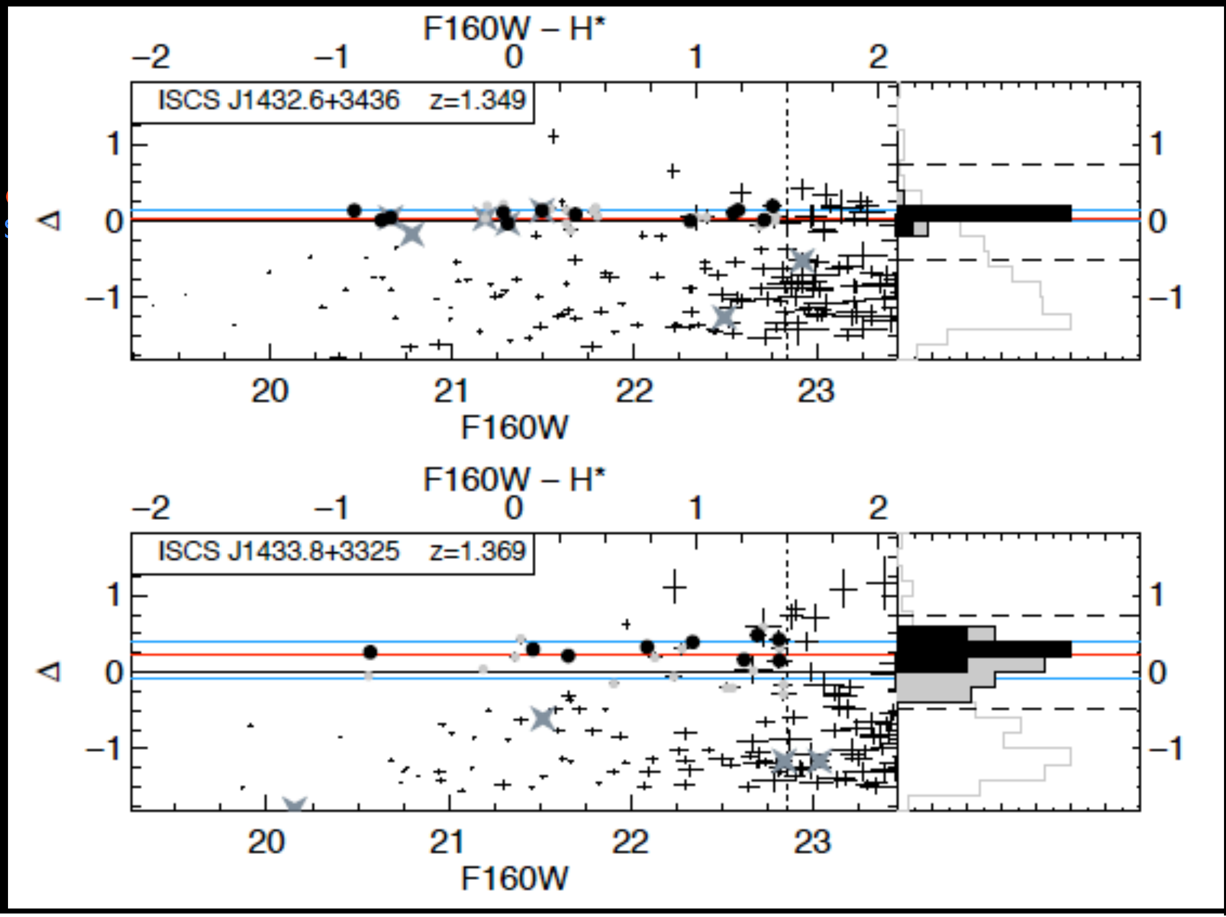
- $H<H^*+1.5$
- Early type (n>2.5)

Mean and total scatter computed using biweight estimator

Photometric scatter computed via bootstraps

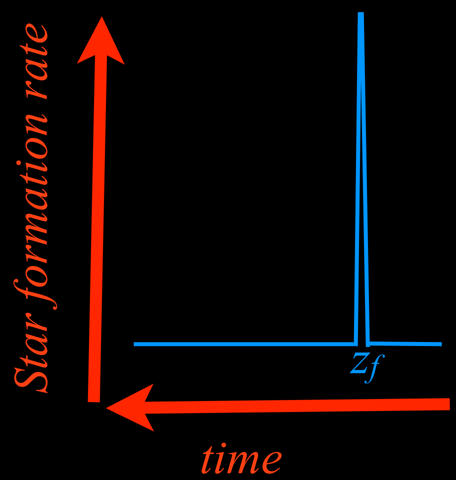
Δ = color offset relative to evolved Coma model for z_f=3

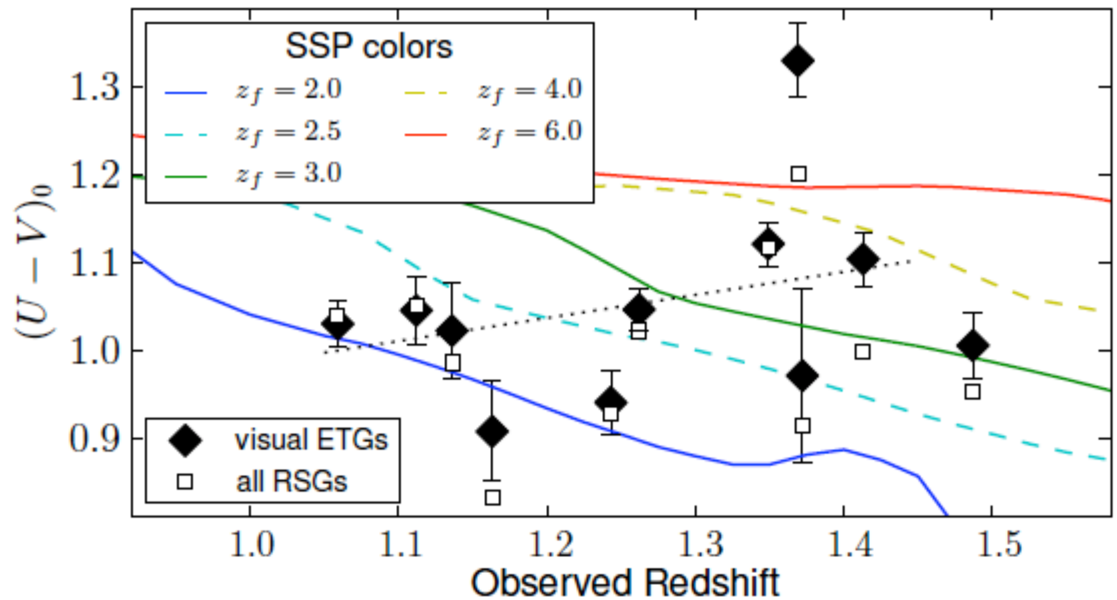
Snyder+ (2012)



Evolution of the Red Sequence

Toy model #1:
Single Burst Model
of Star Formation History





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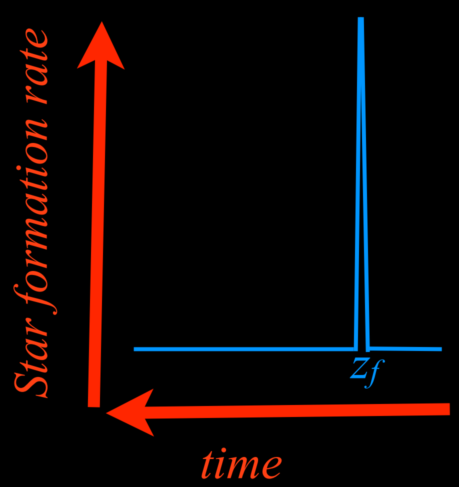
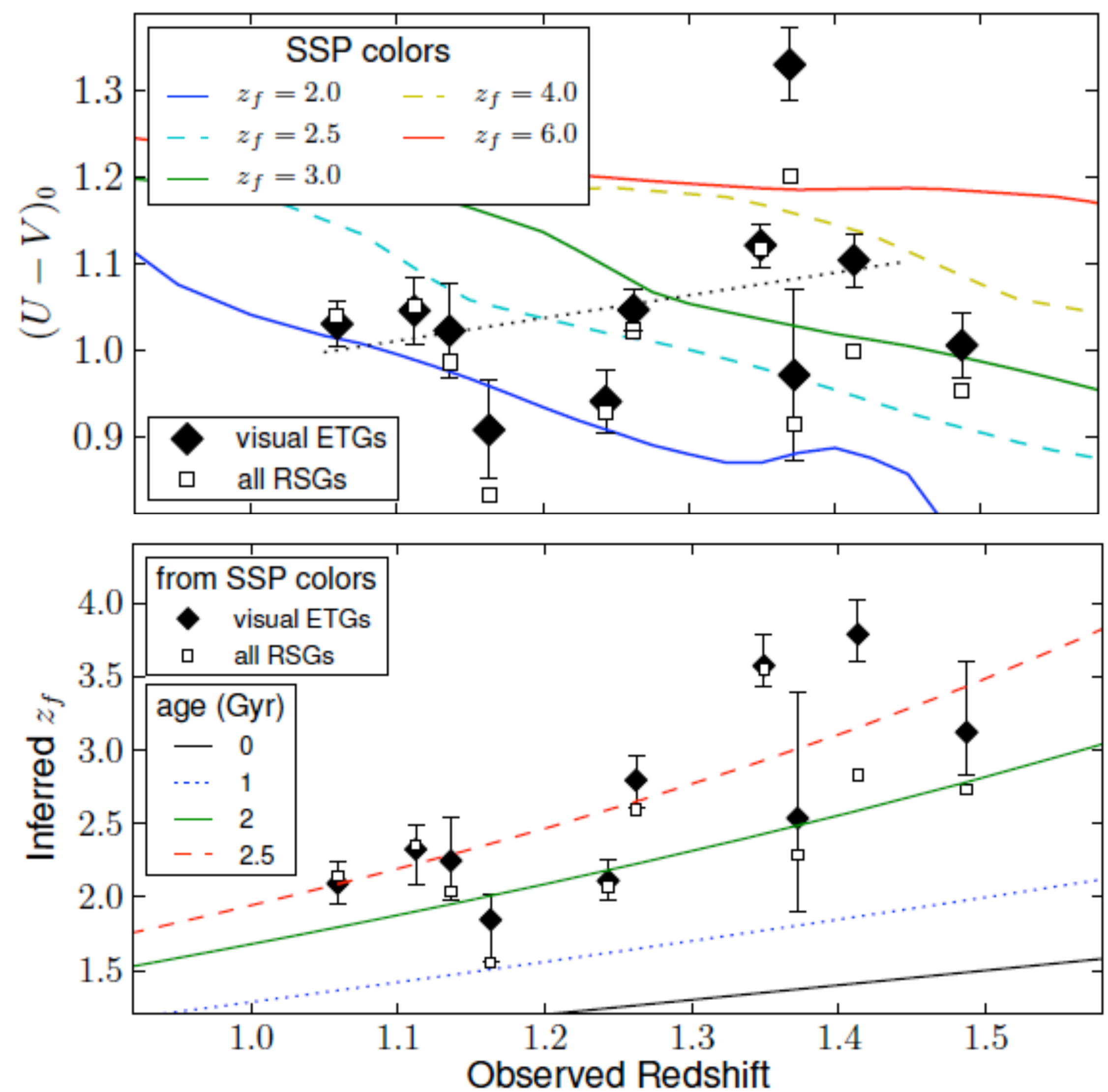


Earlier star formation epoch at higher redshift.

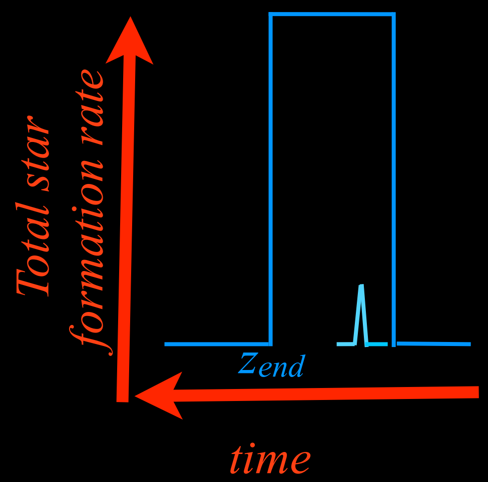


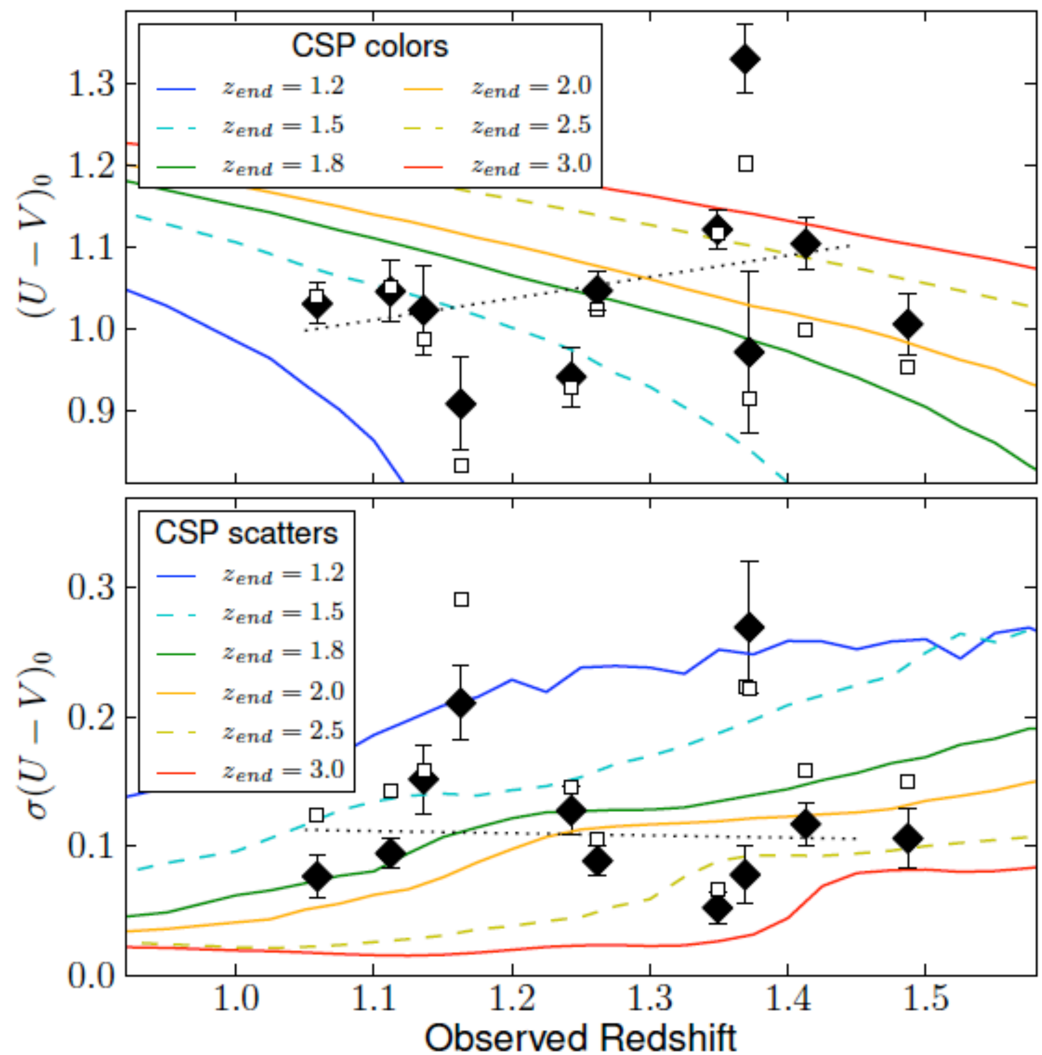
Snyder+ (2012)

Evolution of the Red Sequence

Toy model #2: Extended Cluster Star Formation History

- Individual galaxies have SSPs
- Distribution of star formation epochs continuous until z_{end}





Snyder+ (2012)

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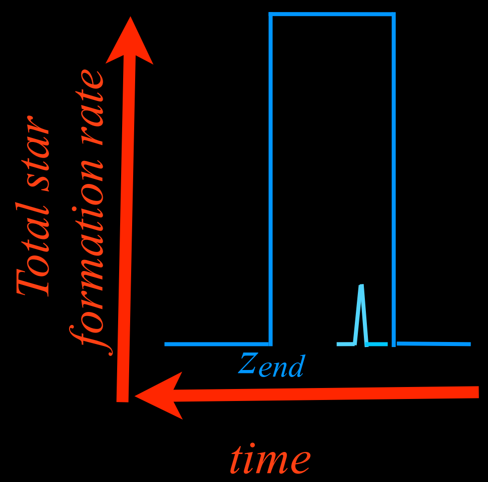
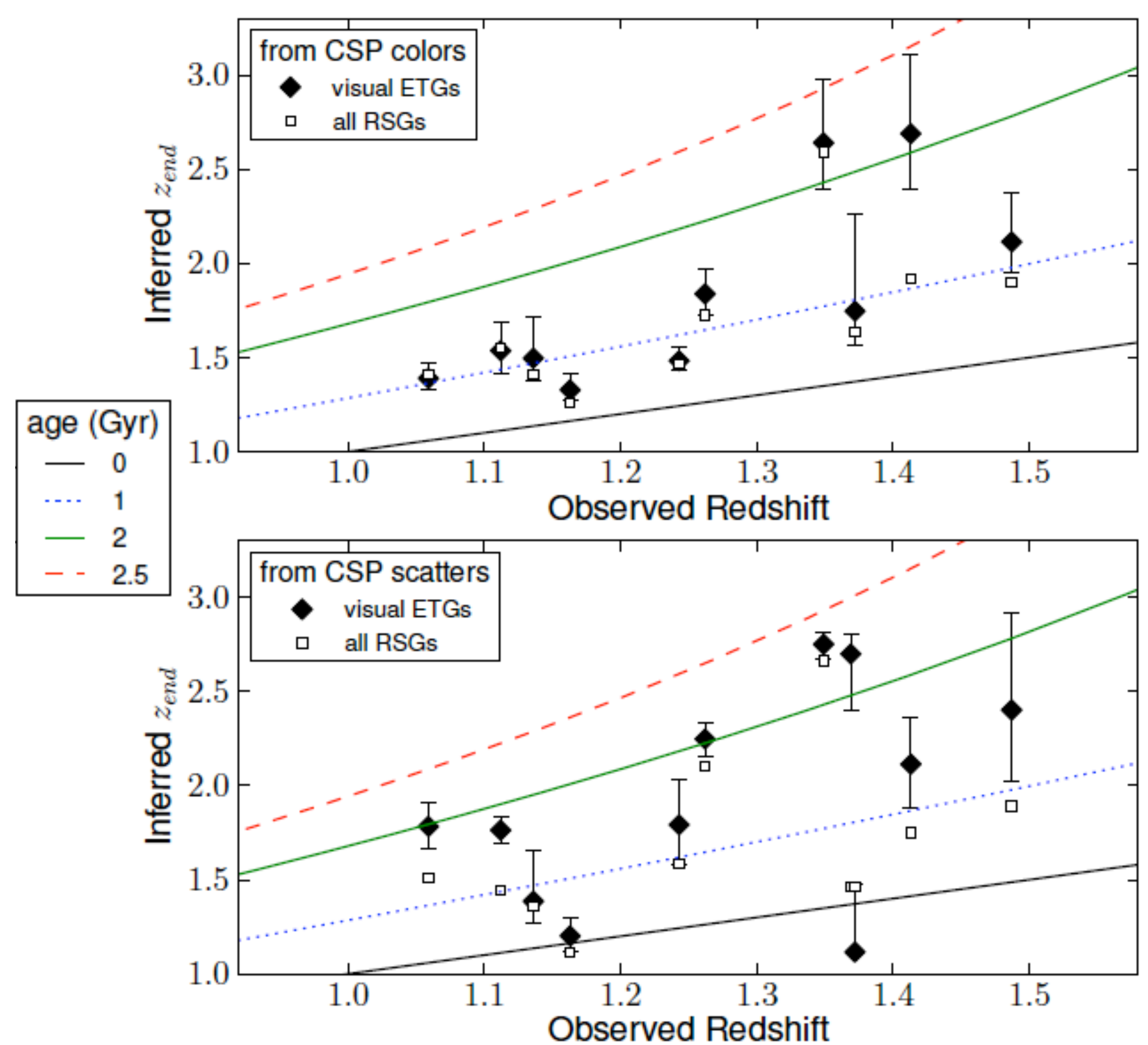


Earlier star formation epoch at higher redshift.

Similar age galaxies on red sequence over full redshift range.

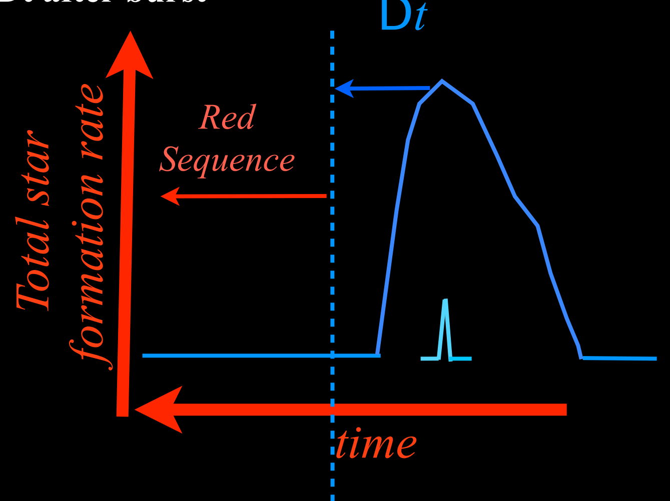


Snyder+ (2012)

Evolution of the Red Sequence

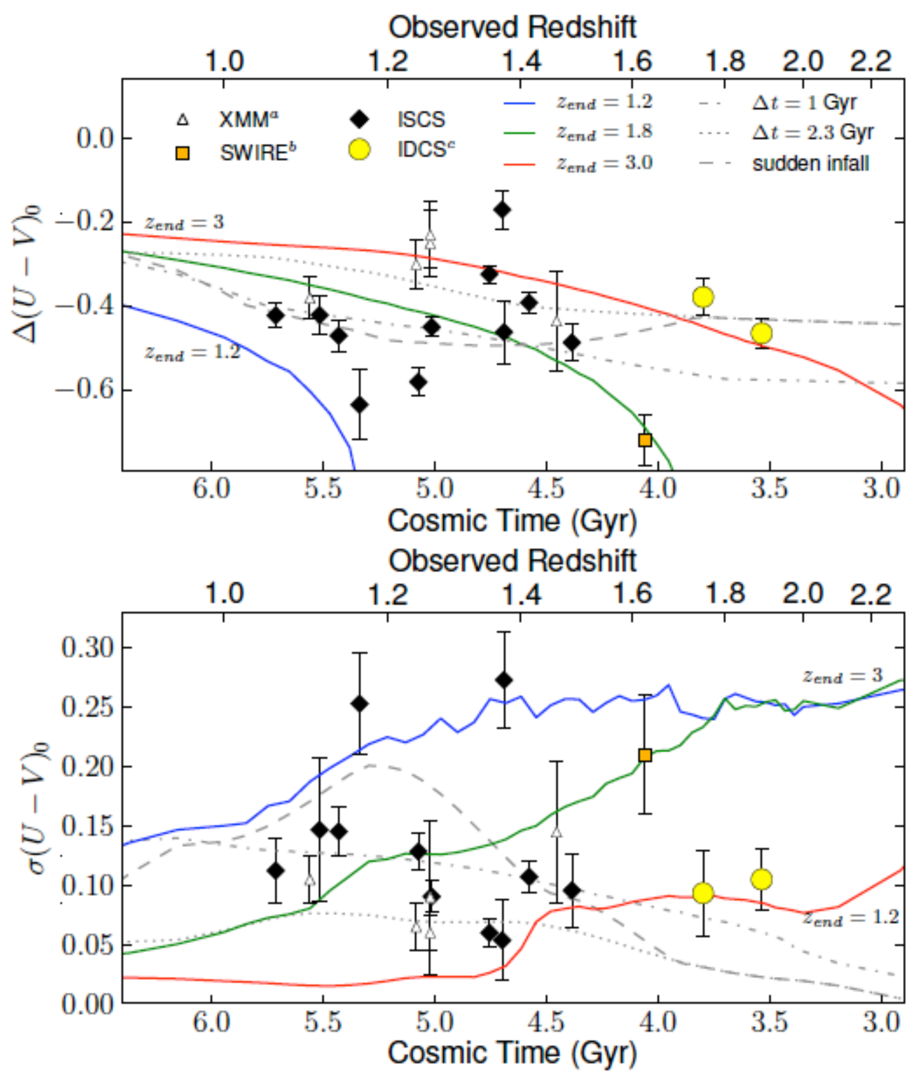
Toy Model #3: Progenitor Bias+ Field SFH

- Single burst for each galaxy
- Galaxy populations follow universal field star formation history
- Galaxies enter red sequence only at time Dt after burst



Models that include this extended formation plus progenitor bias can reproduce general features of red sequence evolution.

"sudden infall" models has D*t increasing with redshift for z>1.2*



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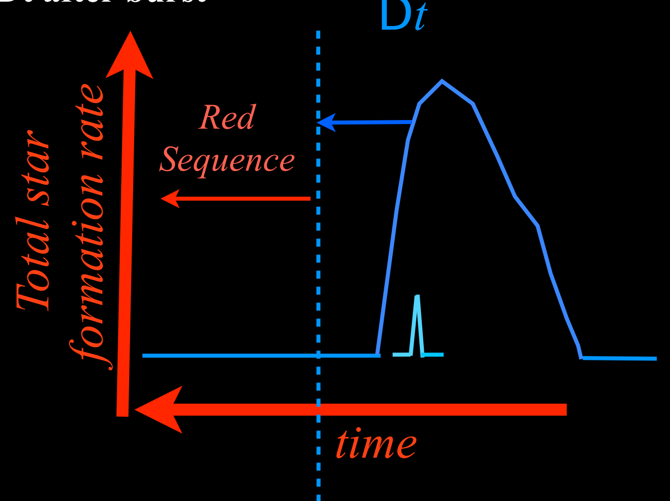

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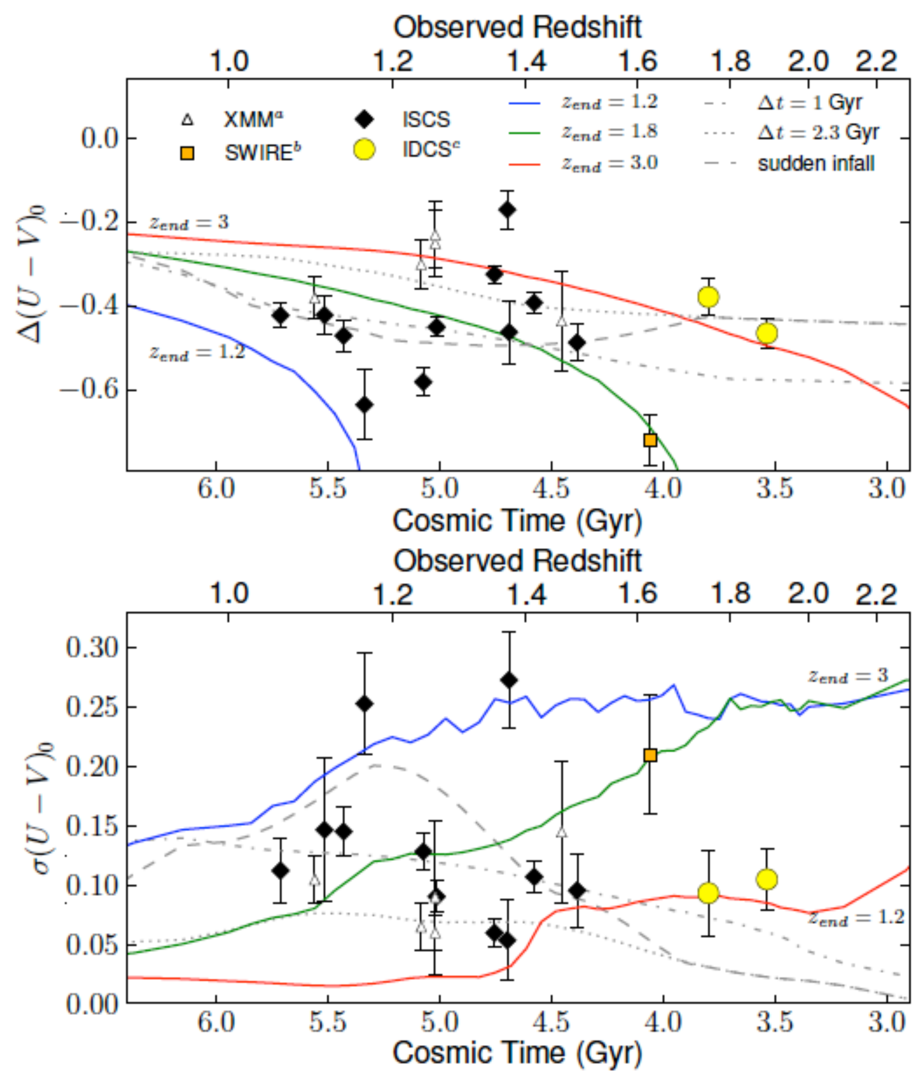

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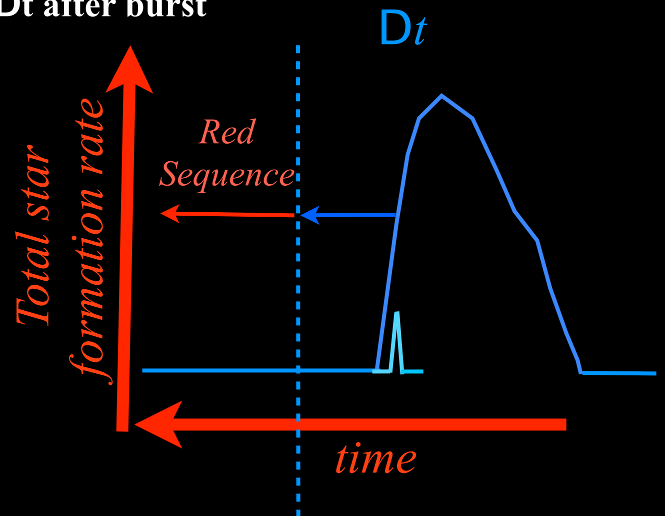

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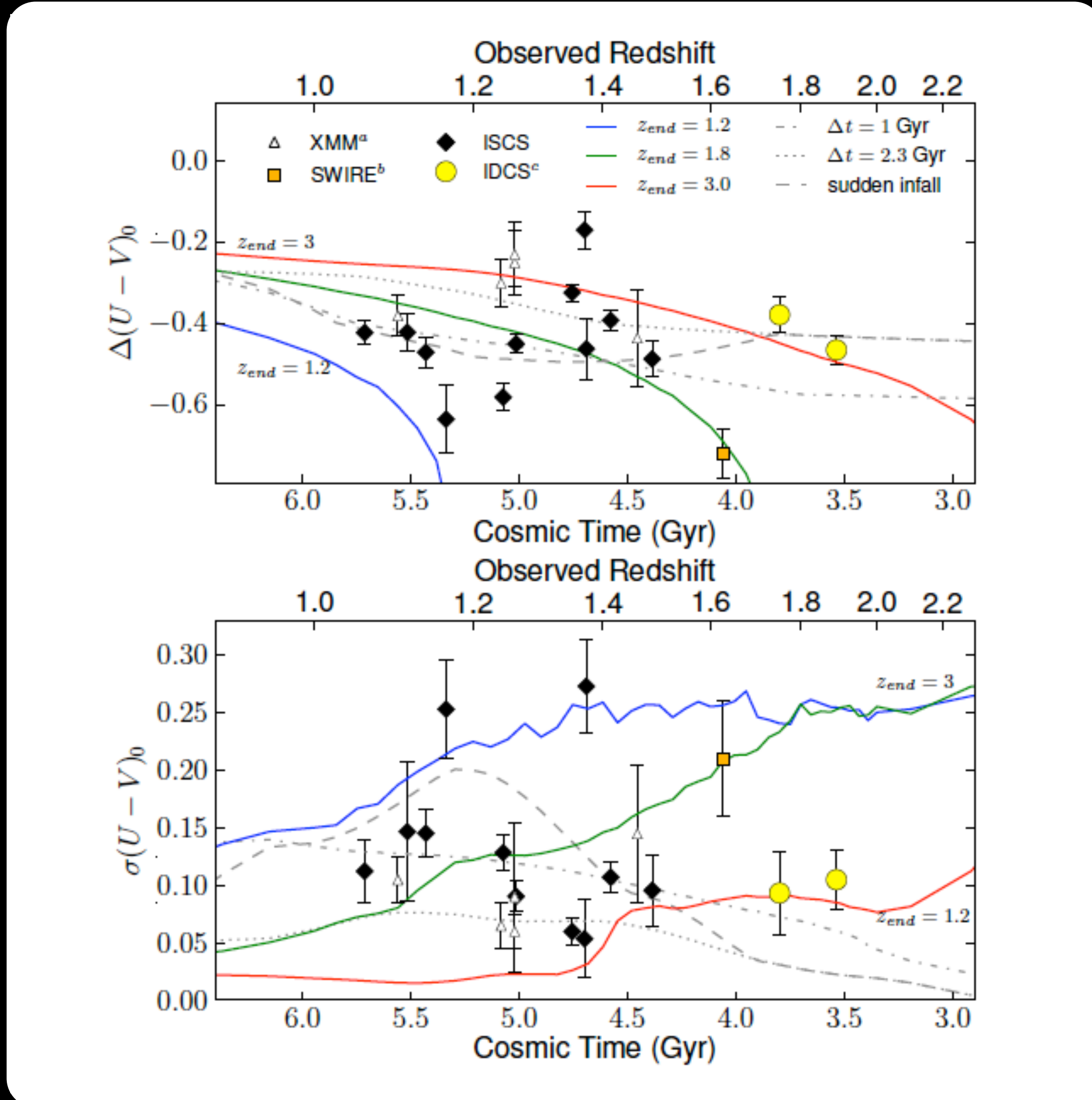
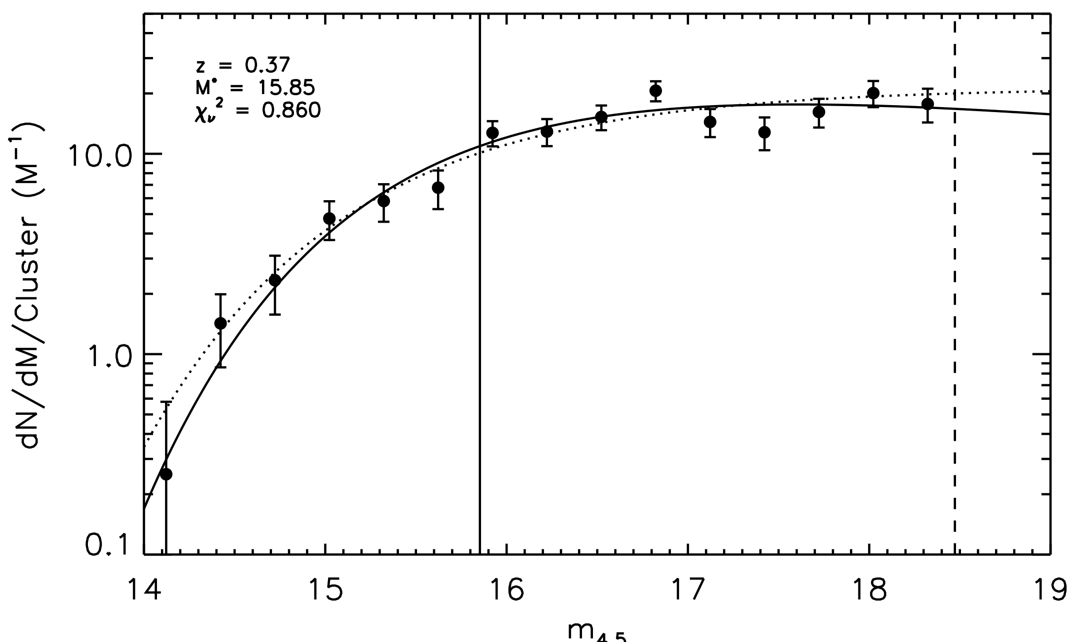


Snyder+ (2012)

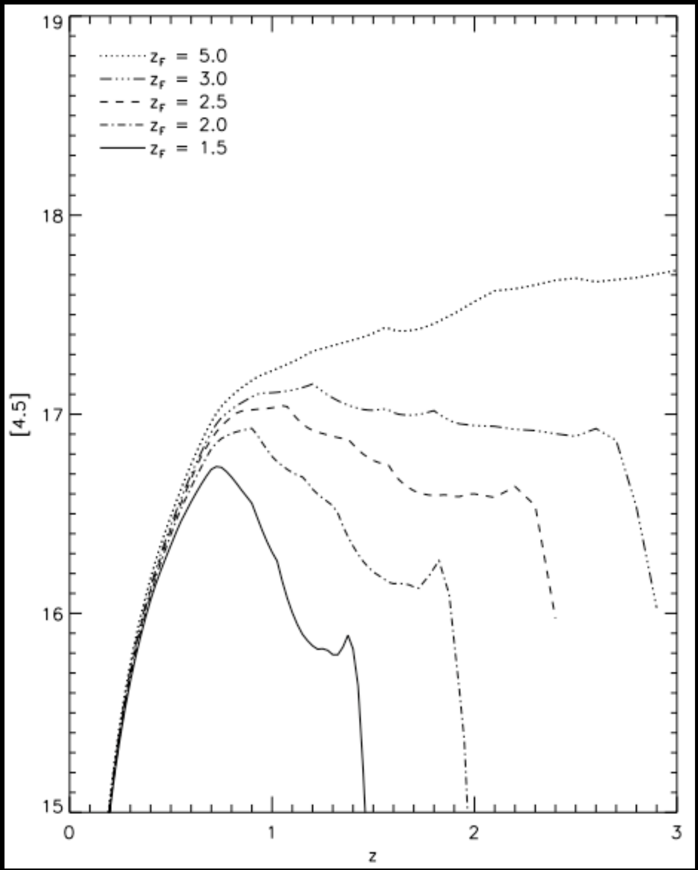
Luminosity Function Evolution

An Ensemble View of Cluster Galaxy Evolution

- **Stacked Luminosity Functions**
  - **335 clusters split into 9 redshift bins**
  - **4.5 mm galaxy selection**
  - **Cluster members: r<1.5 Mpc and >30% probability that redshift is within 0.06(1+z) of cluster**
  - **Maximum likelihood LF fitting**



Mancone+ 2010



The rate of LF evolution depends upon:

1. Mean stellar age
2. Galaxy assembly history

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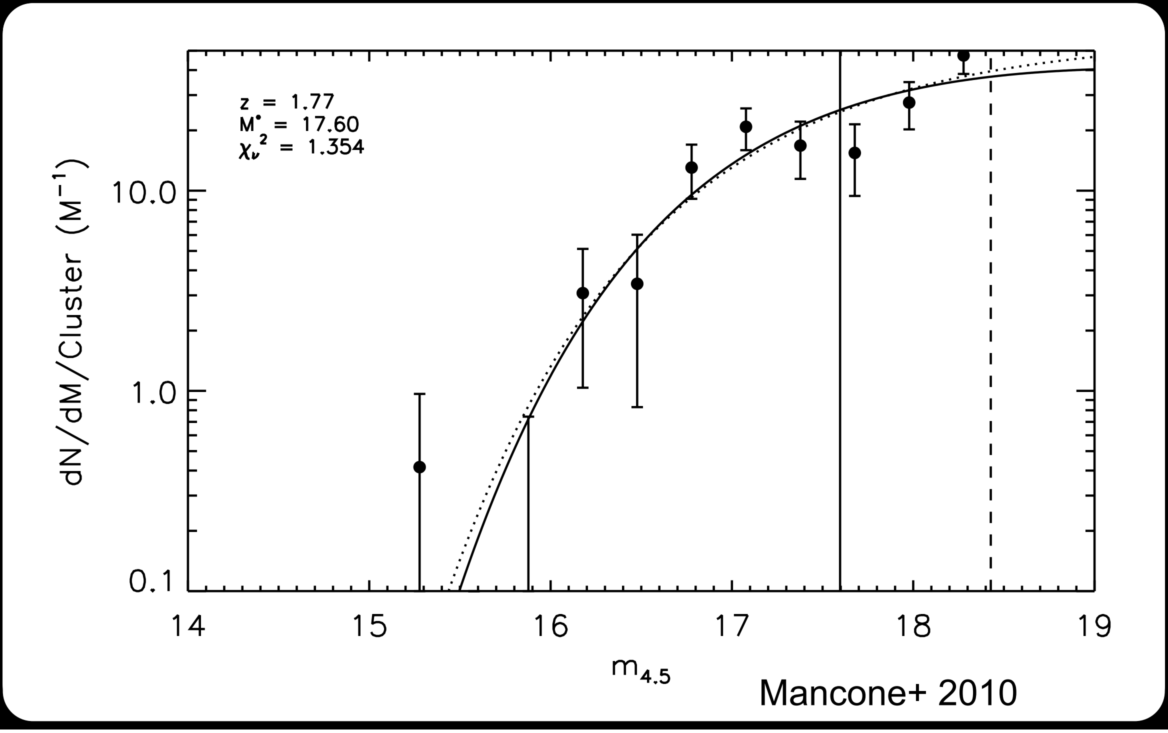

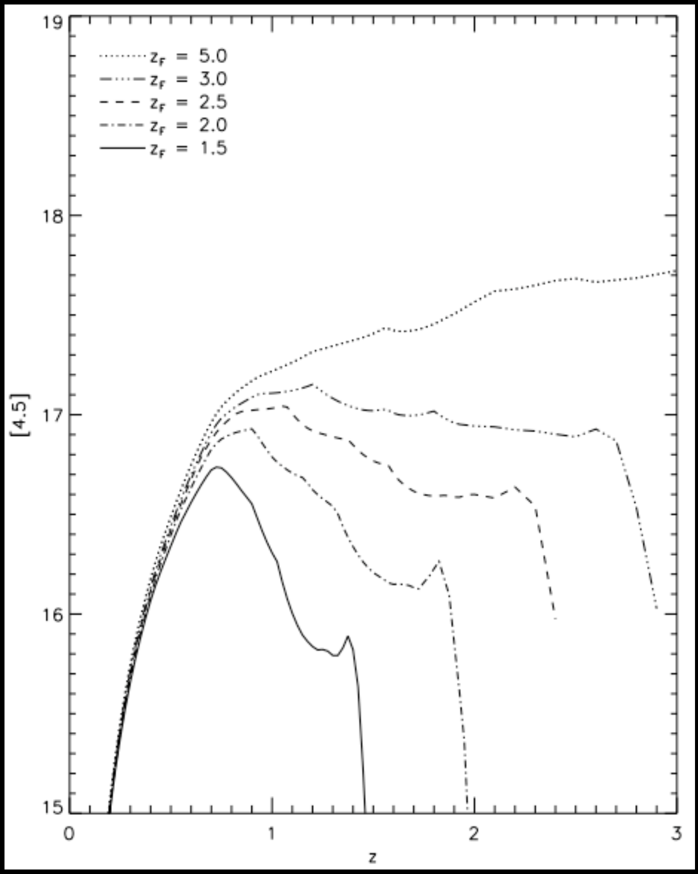

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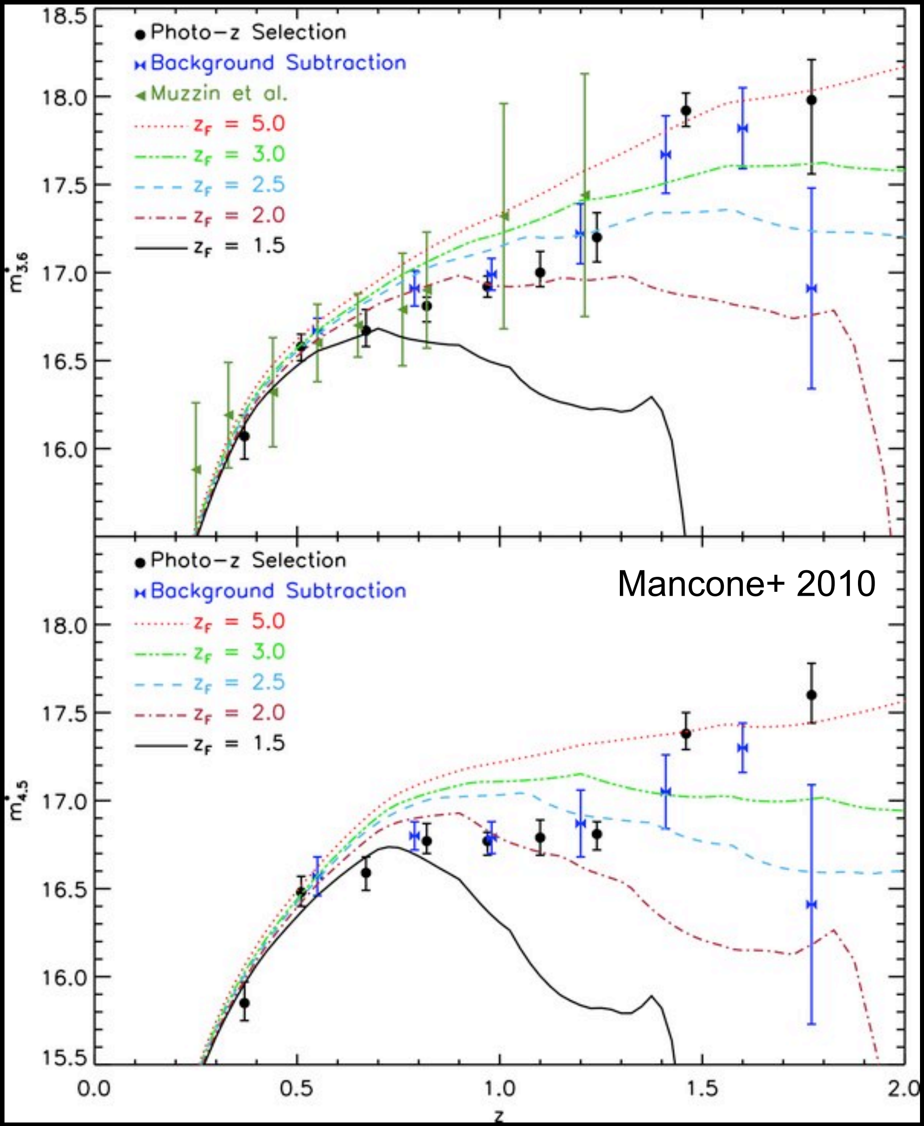
Luminosity Function Evolution

Comparing to Models

(Toy Model #1)



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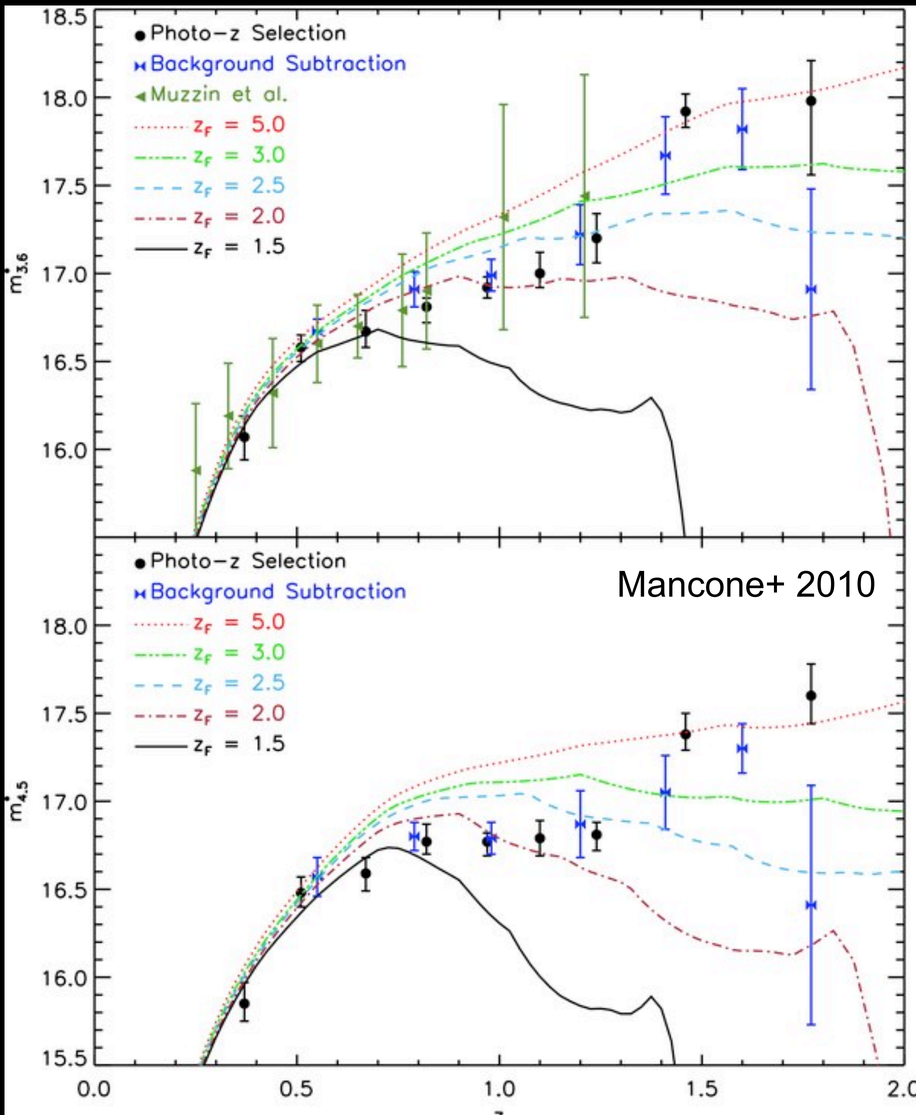
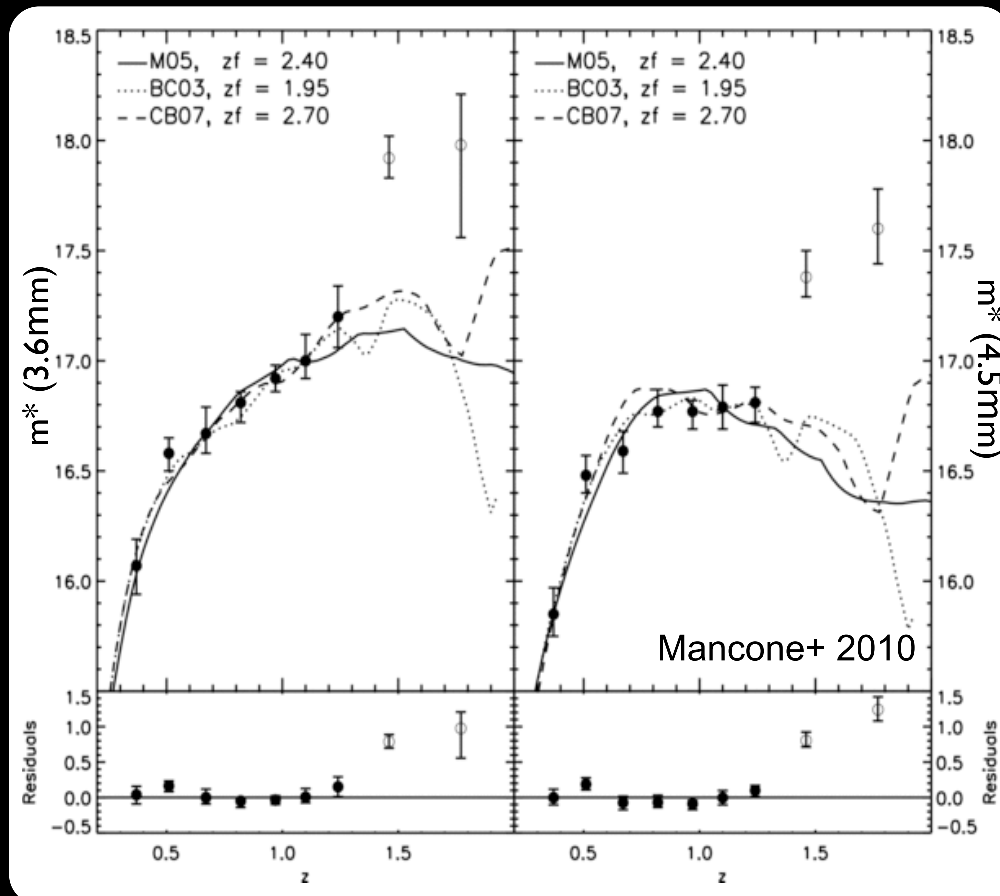


Departure from passive evolution at z~1.3



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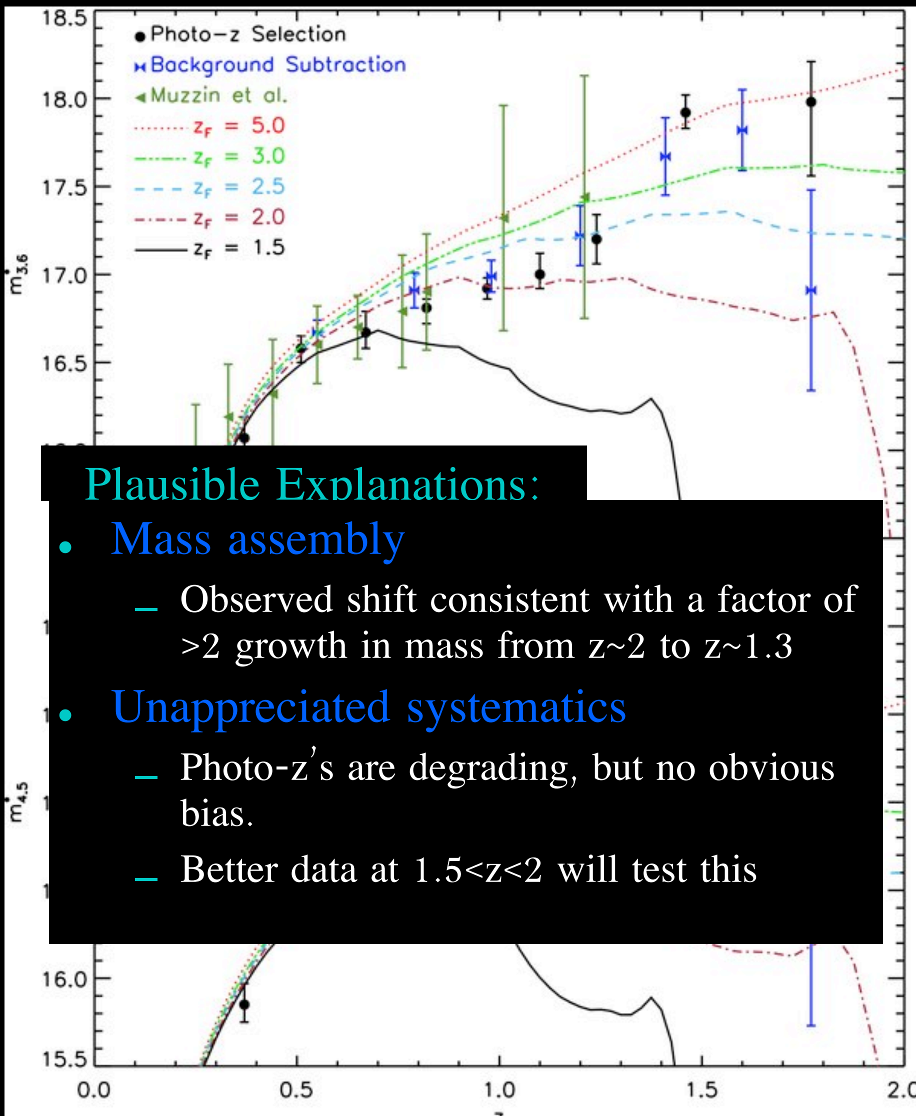
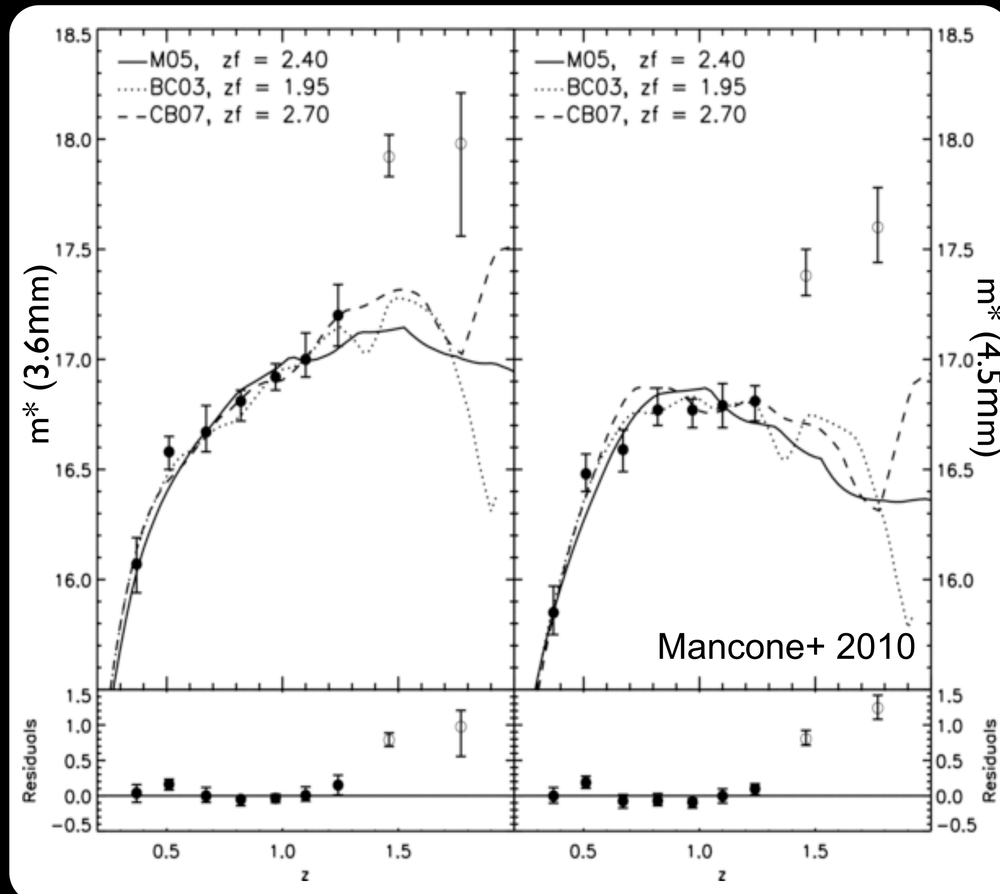


Plausible Explanations:

- Mass assembly
  - Observed shift consistent with a factor of >2 growth in mass from z~2 to z~1.3
- Unappreciated systematics
  - Photo-z's are degrading, but no obvious bias.
  - Better data at 1.5<z<2 will test this

Comparing to Models
(Toy Model #1)

Departure from passive evolution at z~1.3

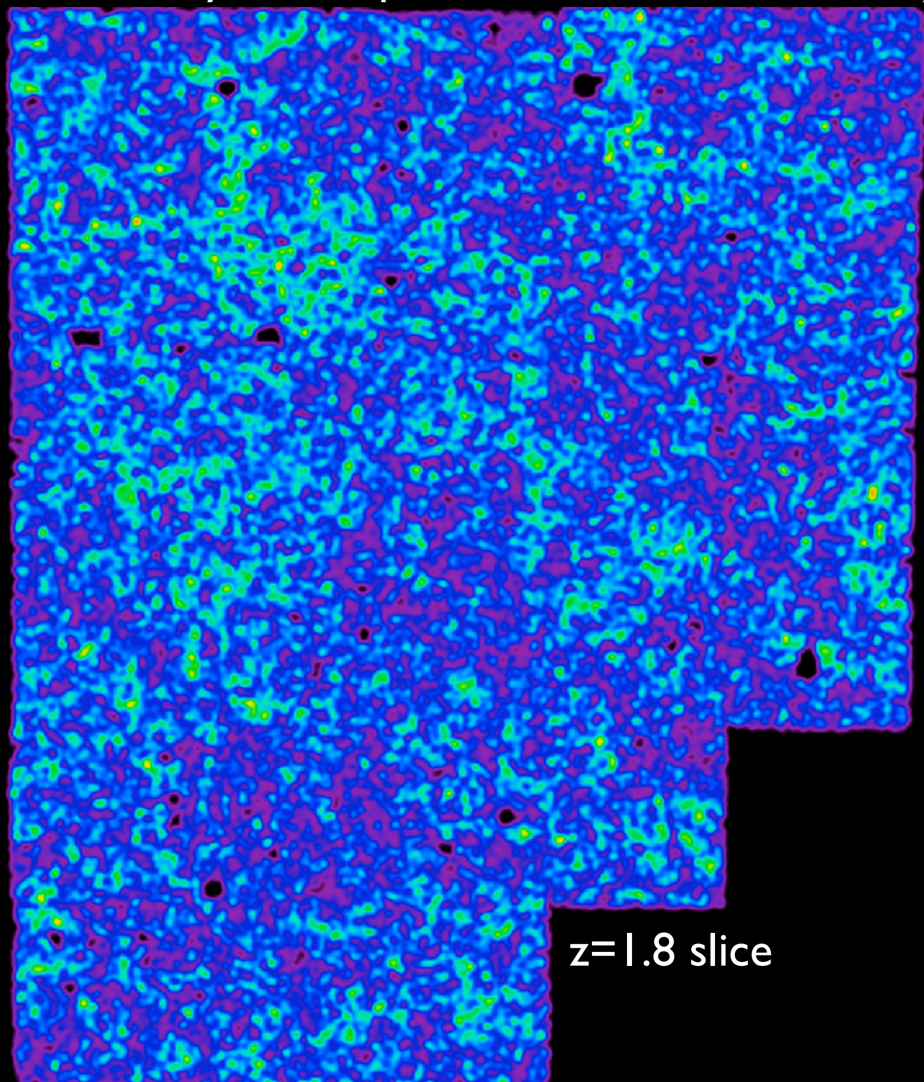


Pushing to higher redshift

The IRAC Deep Cluster Survey (IDCS)

- Key New Ingredients:
  - Spitzer Deep Wide-Field Survey (SDWFS)
    - Factor of 4 increase in exposure time
  - Infrared Bootes Imaging Survey (IBIS)
    - JHKs over full field
  - Refined search algorithm

Preliminary search performed with SDWFS only



z=1.8 slice

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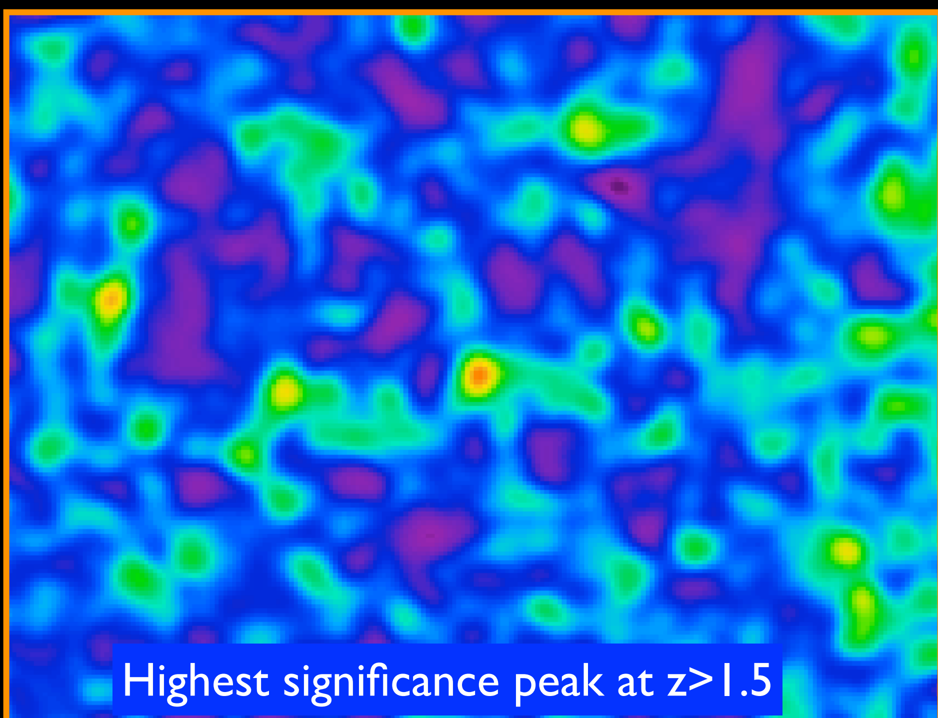

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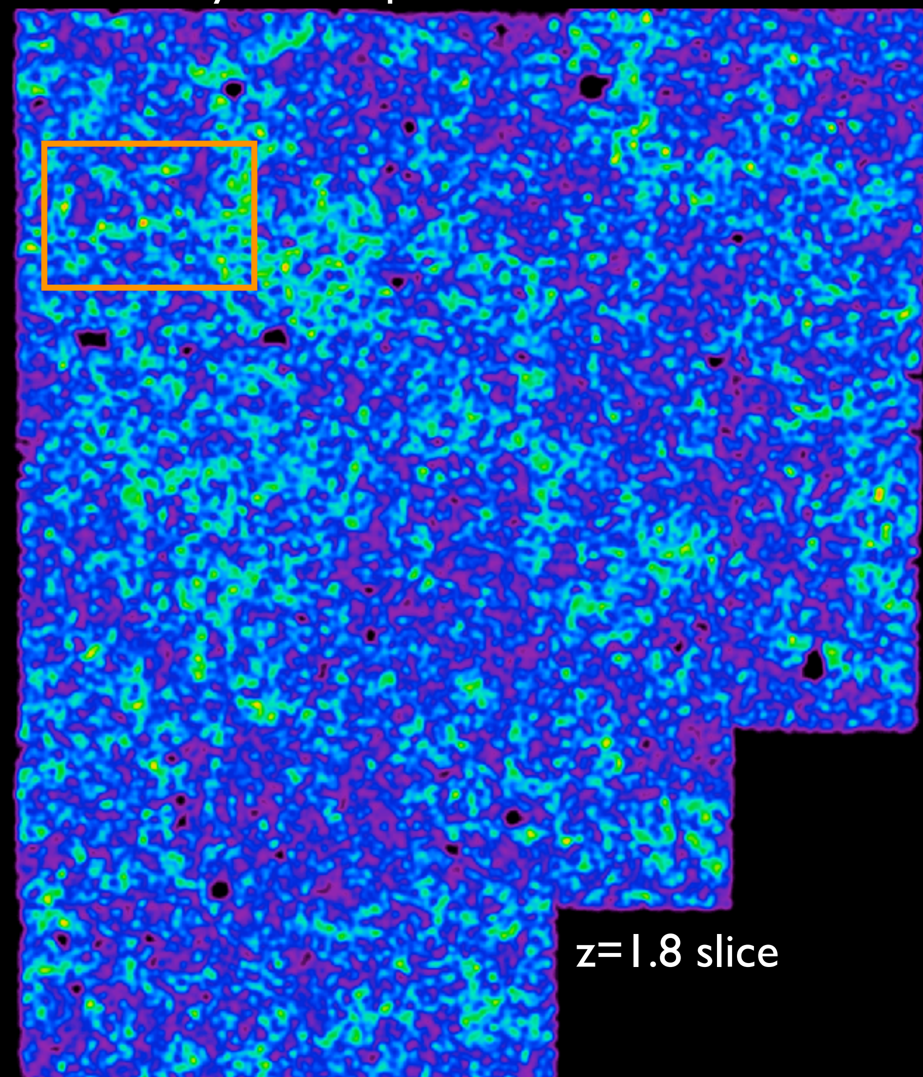

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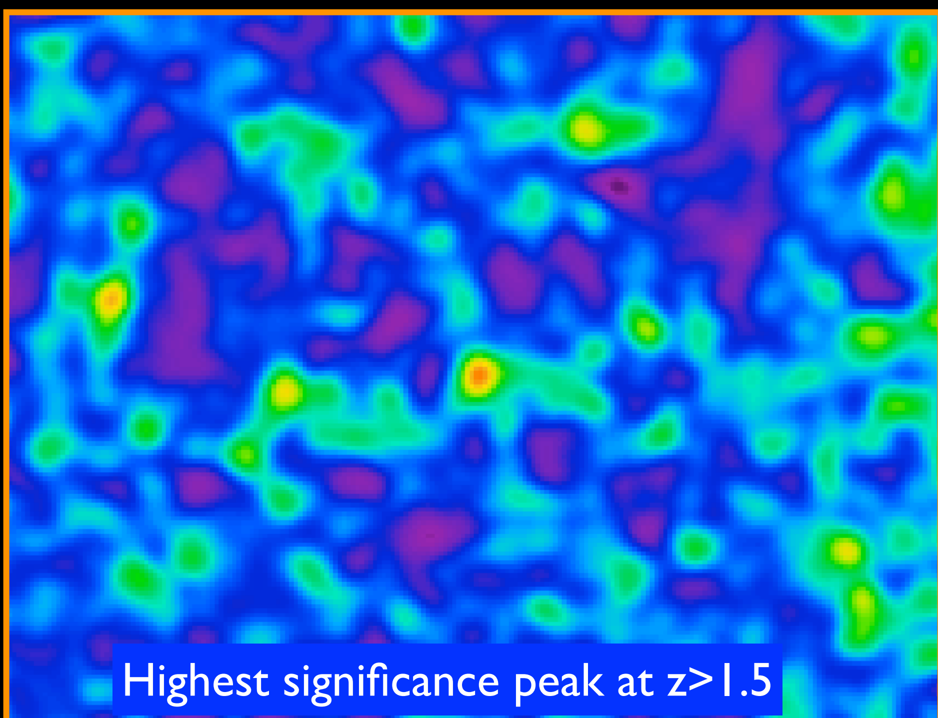

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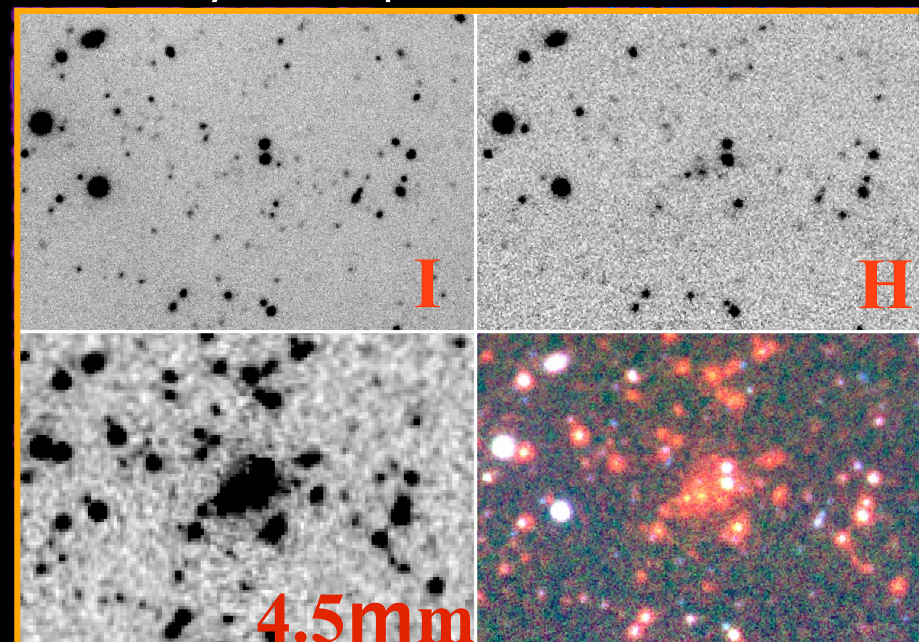
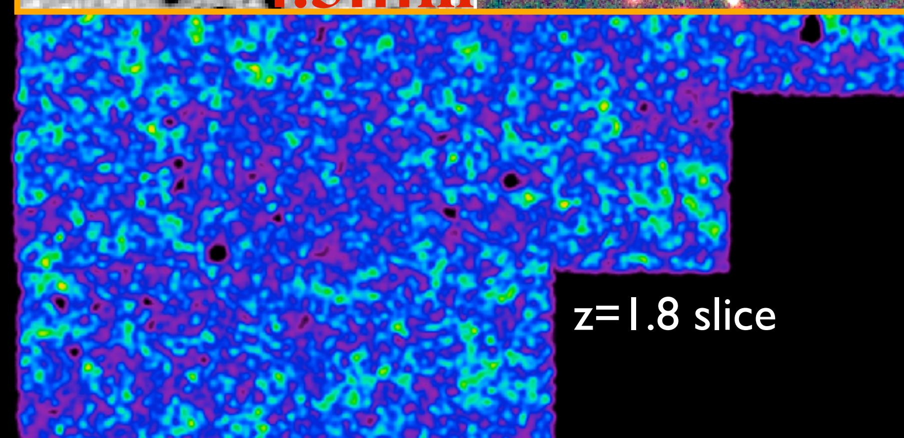


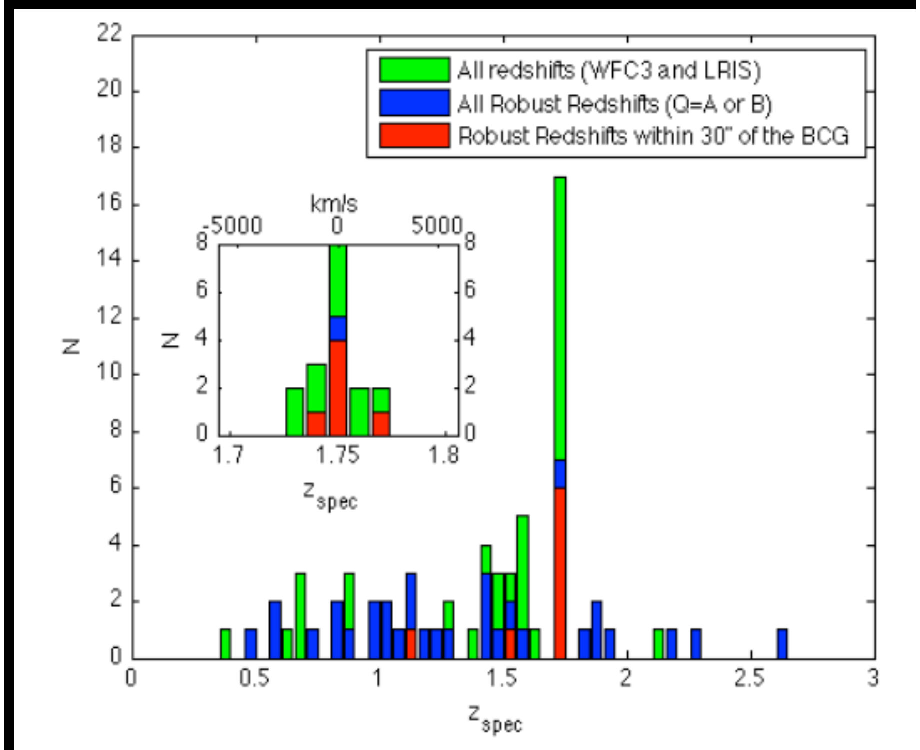


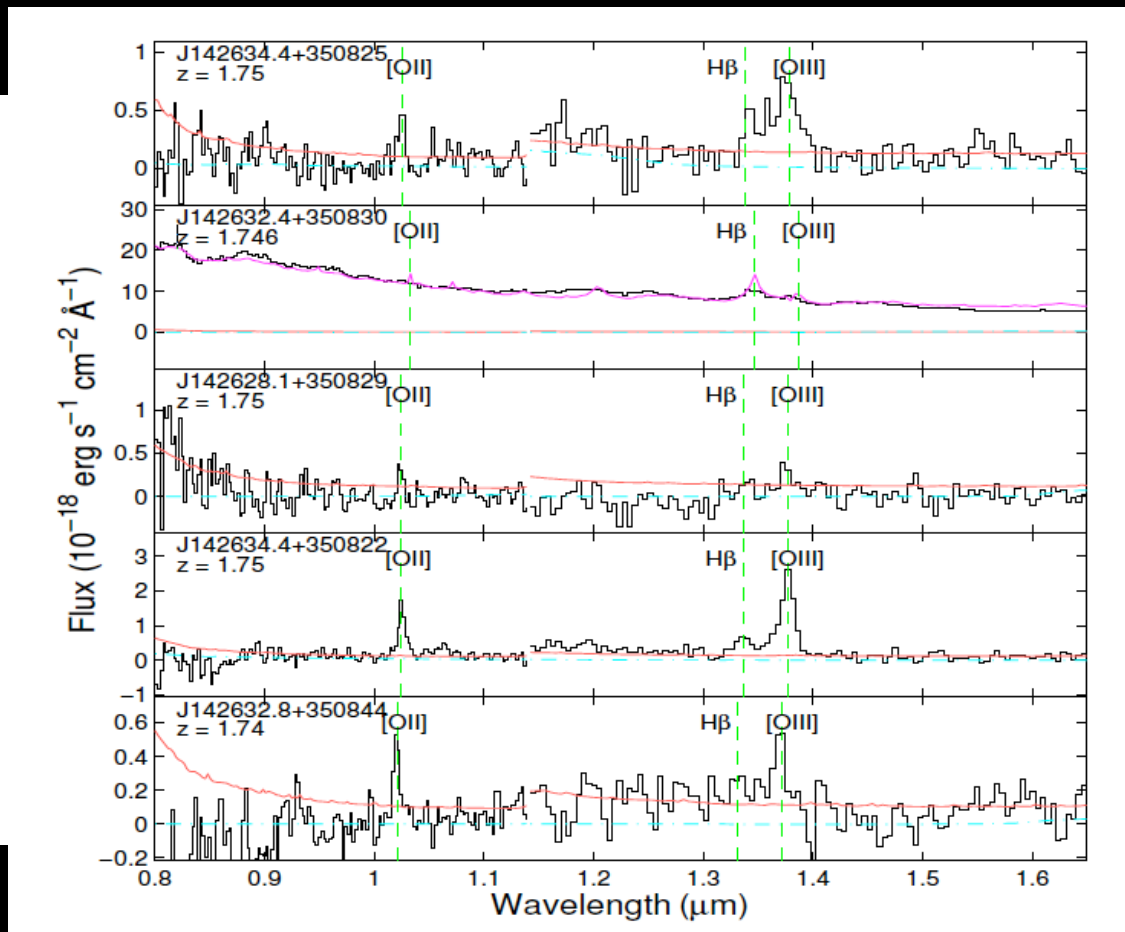
z=1.8 slice

IDCS J1426.5+3508: Confirmation

Confirmation Spectroscopy with Keck/LRIS + WFC3 Grism

- z=1.75
- 7 spec-z confirmed members (6 within 30" of BCG), including 1 QSO
- 10 additional lower quality grism spectra consistent with cluster redshift.





Brodwin+ (2012)

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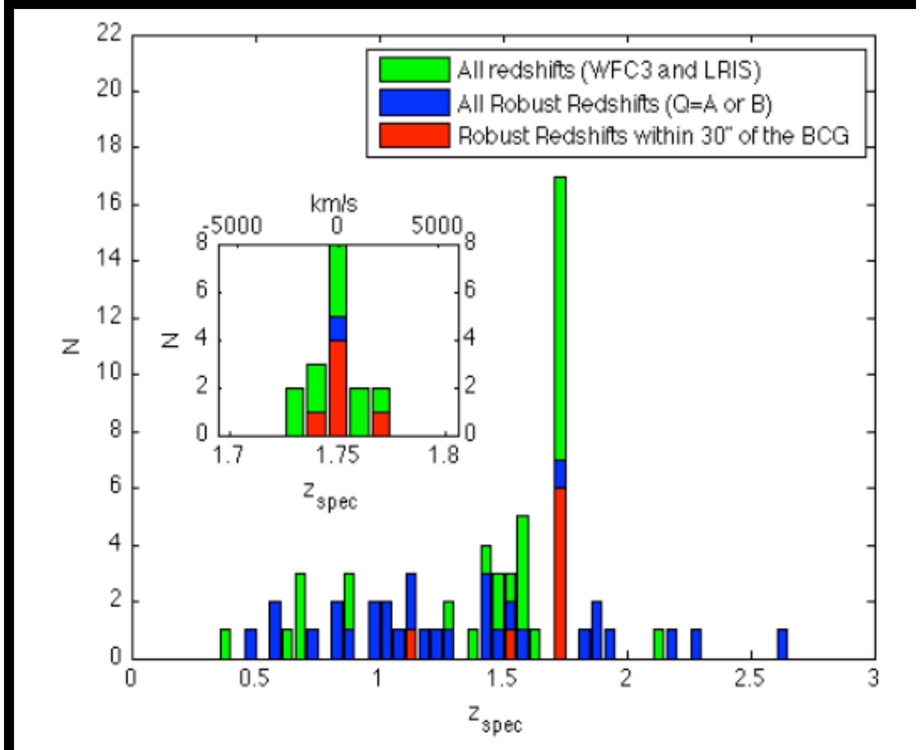
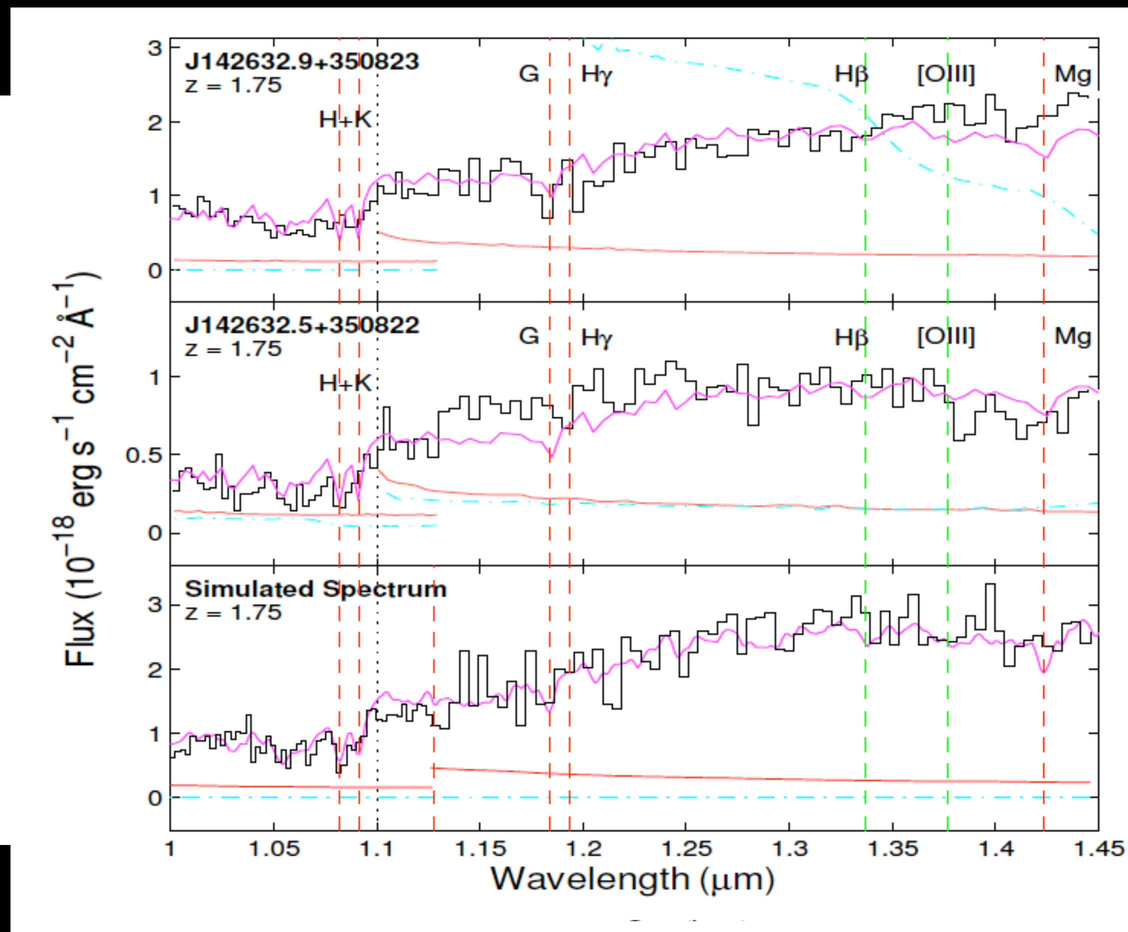


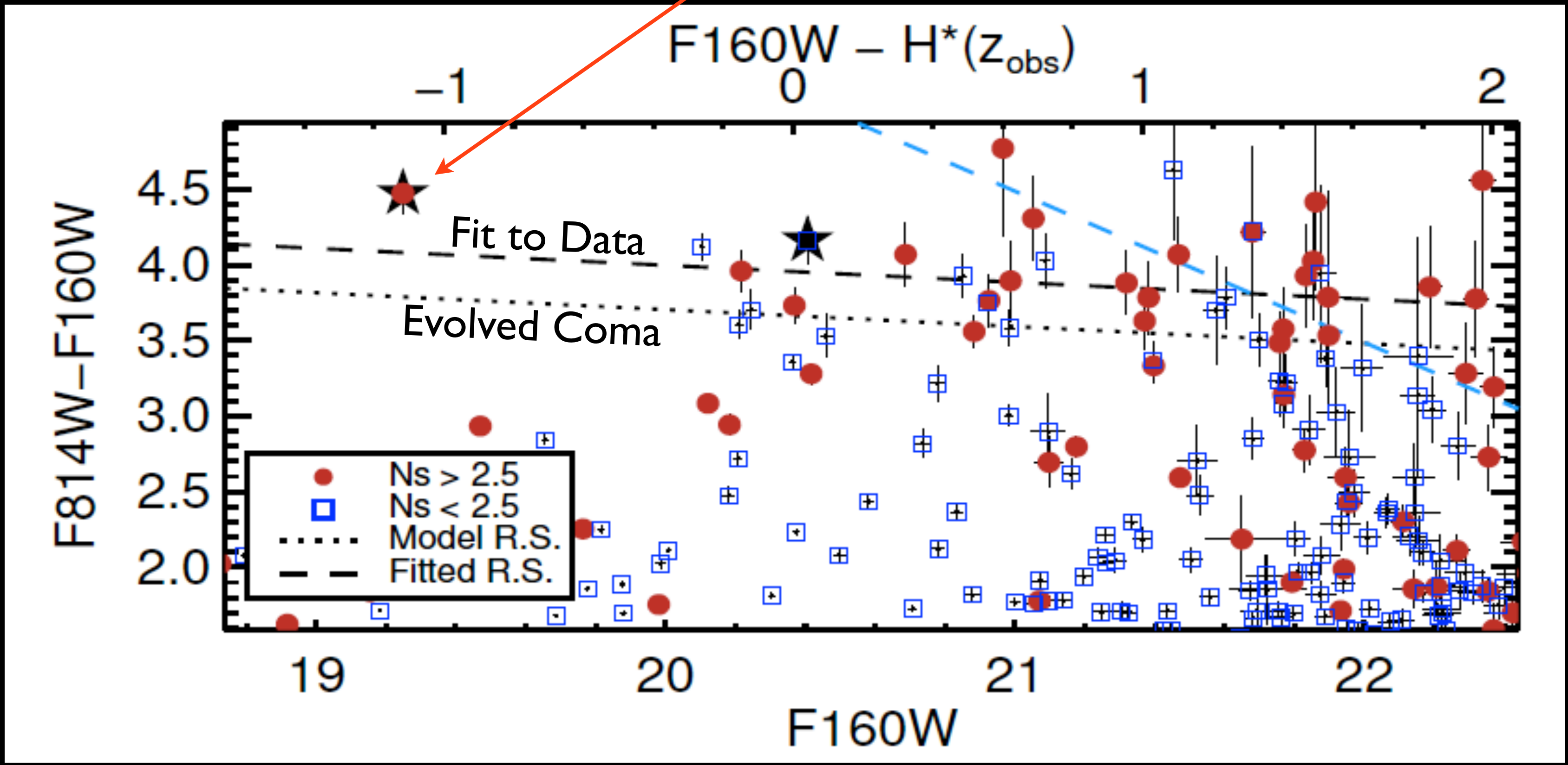


Brodwin+ (2012)

IDCS J1426.5+3508: Galaxy Properties

Red Sequence

BCG: H*+2, r_e=18 kpc



Starred symbols are spectroscopically confirmed members from Keck

Stanford+ (2012)

Circles: n>2.5

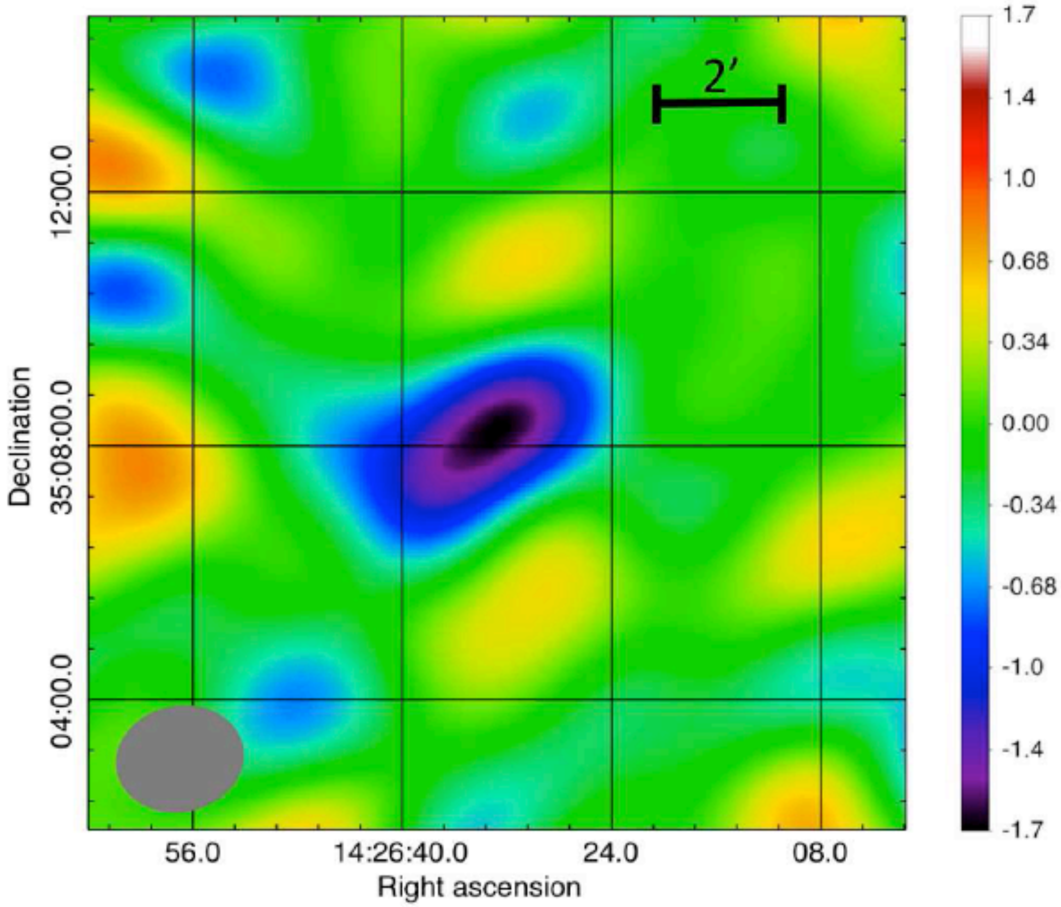
Squares: n<2.5

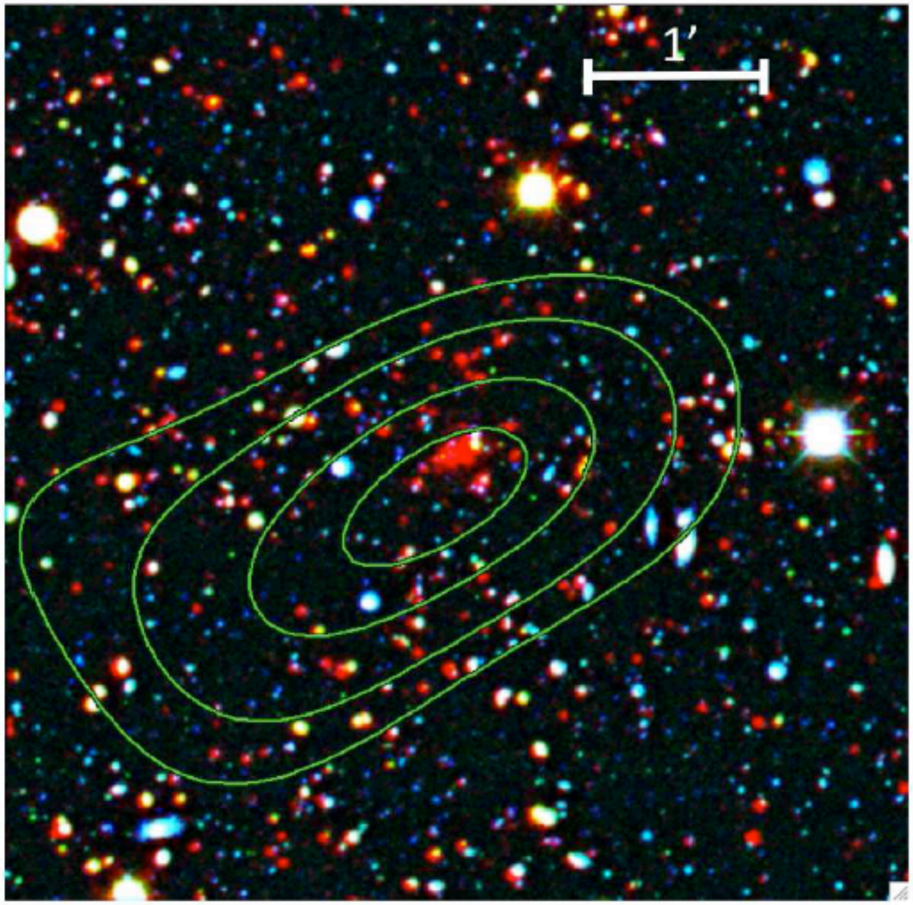
IDCS J1426.5+3508: Mass

X-ray detection in 5 ks archival Chandra image ⇒ M_{200}~$5.5 \times 10^{14}\ M_{\odot}$
5.3 s SZ detection with CARMA/SZA ⇒ M_{200}~$4.1 \pm 1.1 \times 10^{14}\ M_{\odot}$

Most massive known cluster at z>1.4

Brodwin+ (2012a)



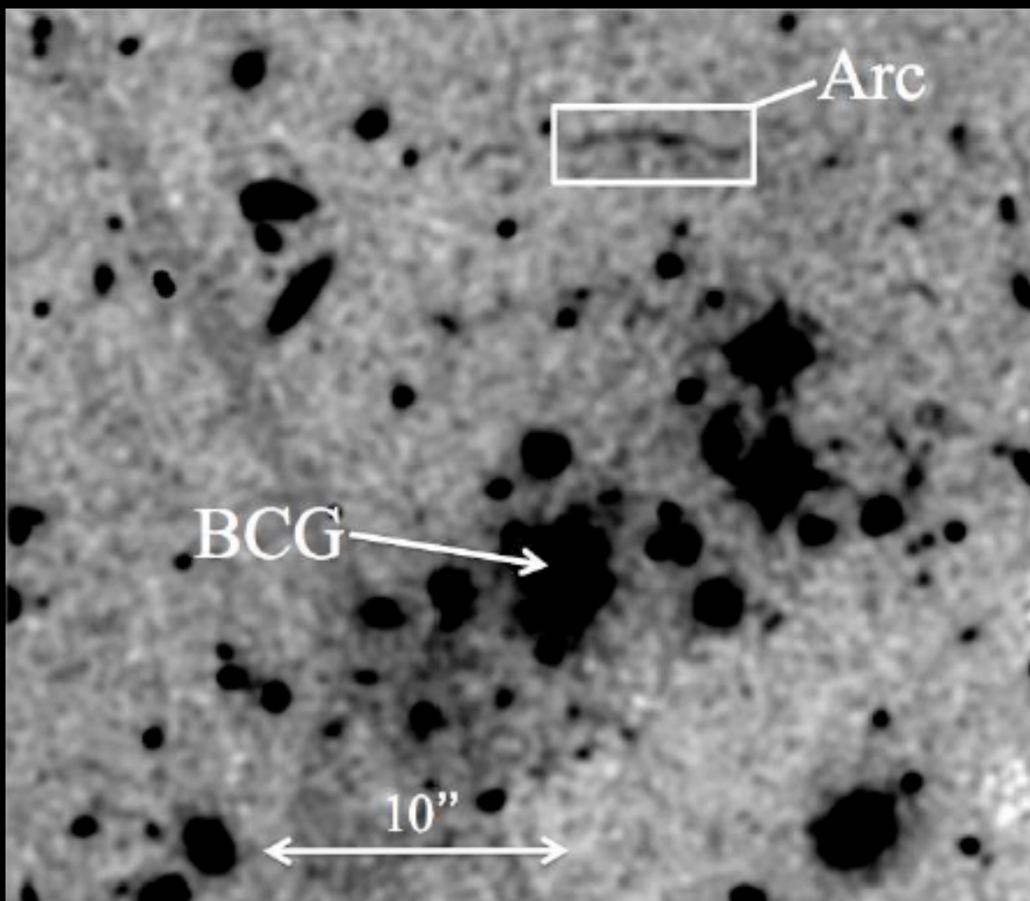


IDCS J1426.5+3508: Strong Lensing

Another surprise —a giant arc!

Length-to-width ratio >>10 (4.8" long, unresolved width with HST)

Color consistent with star-forming galaxy at z=2-6.



No significant substructure near arc, so enclosed mass reasonably approximated by standard lensing relation:

$$\mathrm{M_{enclosed}} = \pi \Sigma_{\mathrm{c}} \theta_{\mathrm{arc}}^2$$

where

$$\Sigma_c = \frac{c^2}{4\pi G} \frac{D_s}{D_L D_{LS}}$$

...which depends on the unknown redshift of the arc...

The fact that the arc is not a dropout (z<6), implies a lower limit $M_{enclosed}$>0.7x$10^{13}M_\odot$.

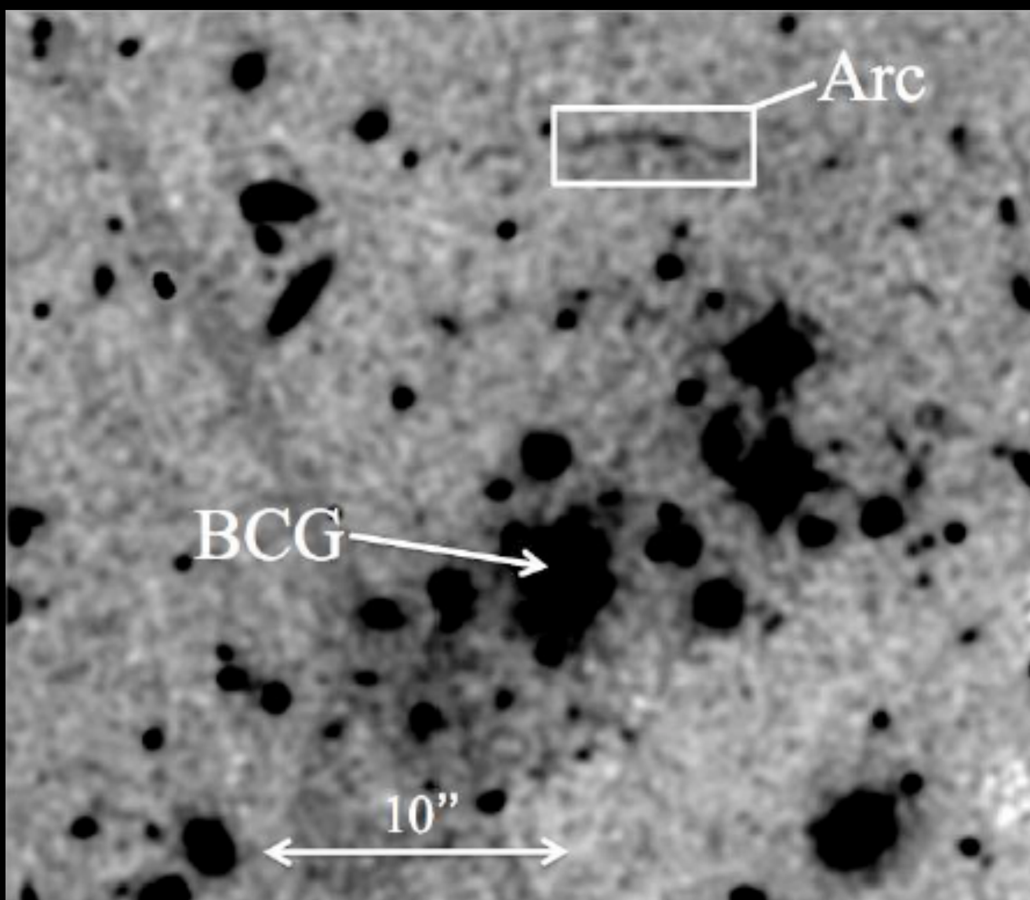
Gonzalez+ (2012b)

IDCS J1426.5+3508: Strong Lensing

Estimating M_{200}

Must assume:

- **Halo concentration prescription**
- **Cluster ellipticity**



IDCS J1426.5+3508: Strong Lensing

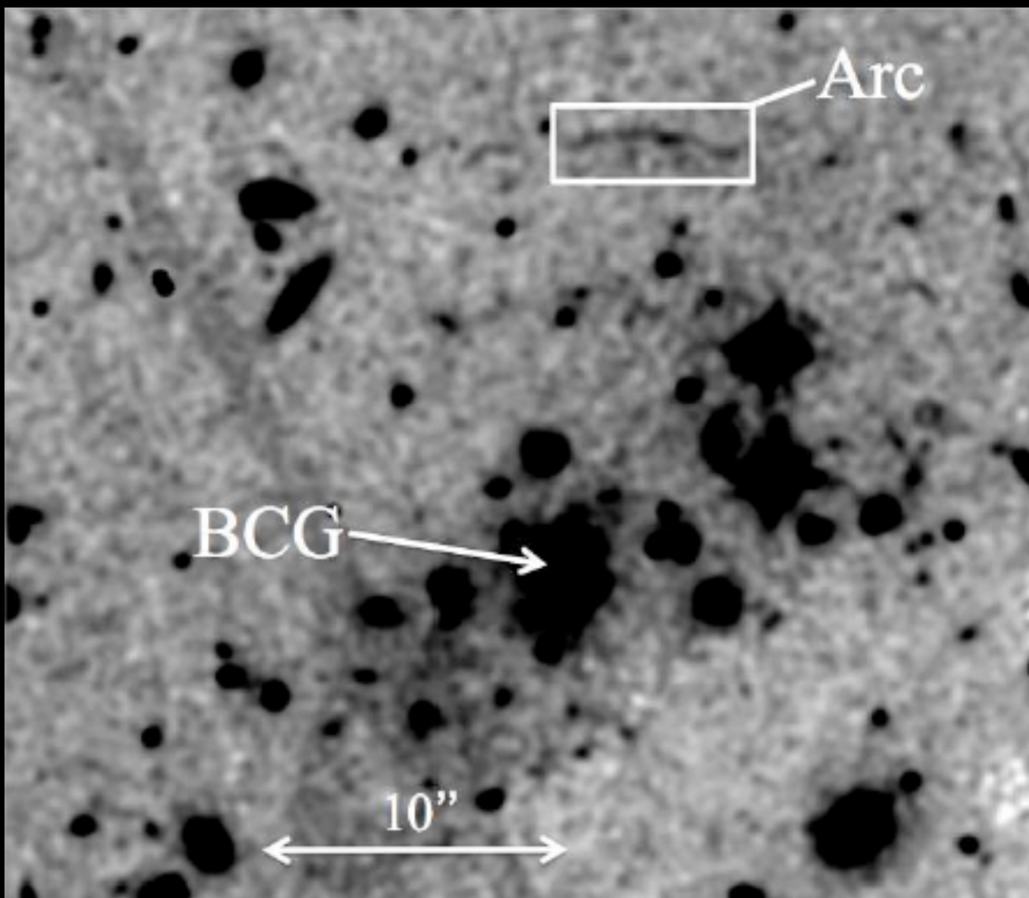
Estimating M_{200}

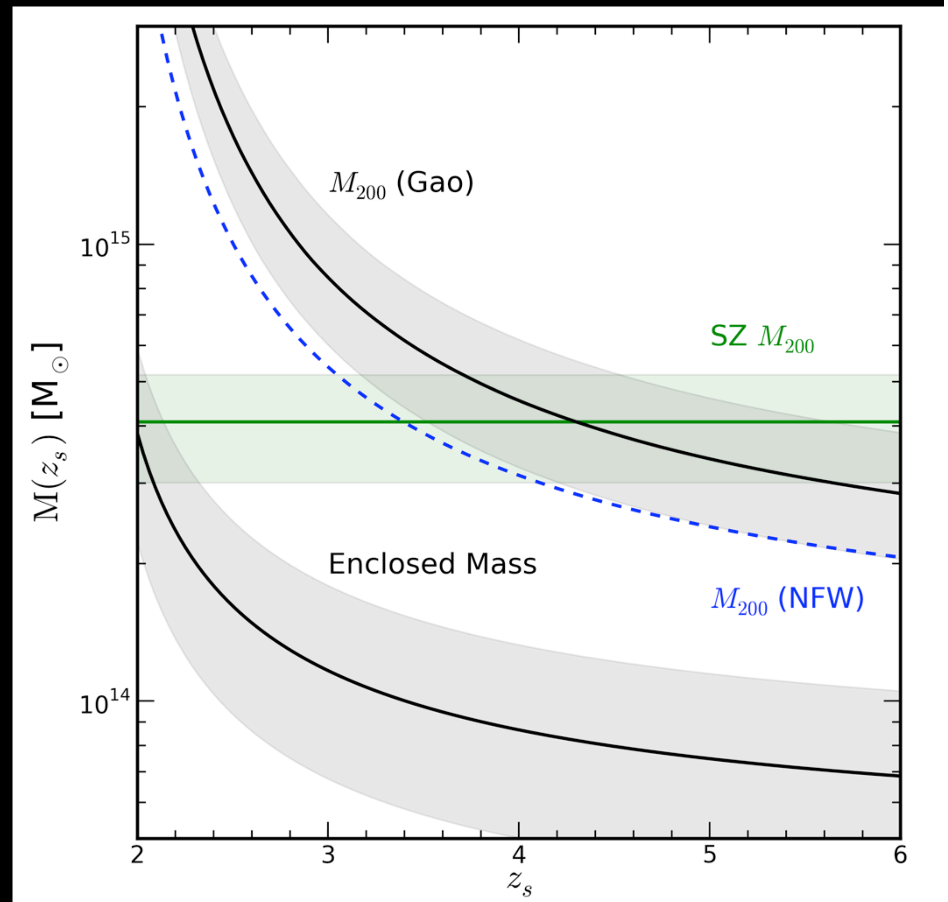
Must assume:

- **Halo concentration prescription**
- **Cluster ellipticity**

SZ and lensing masses roughly consistent for source redshifts $z \gtrsim 3$

Gonzalez+ (2012b)

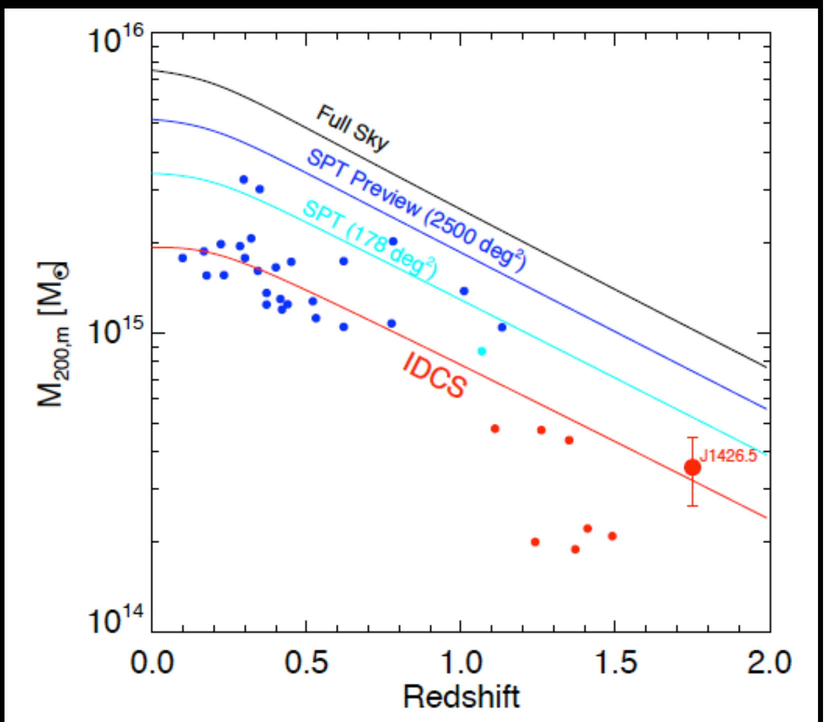




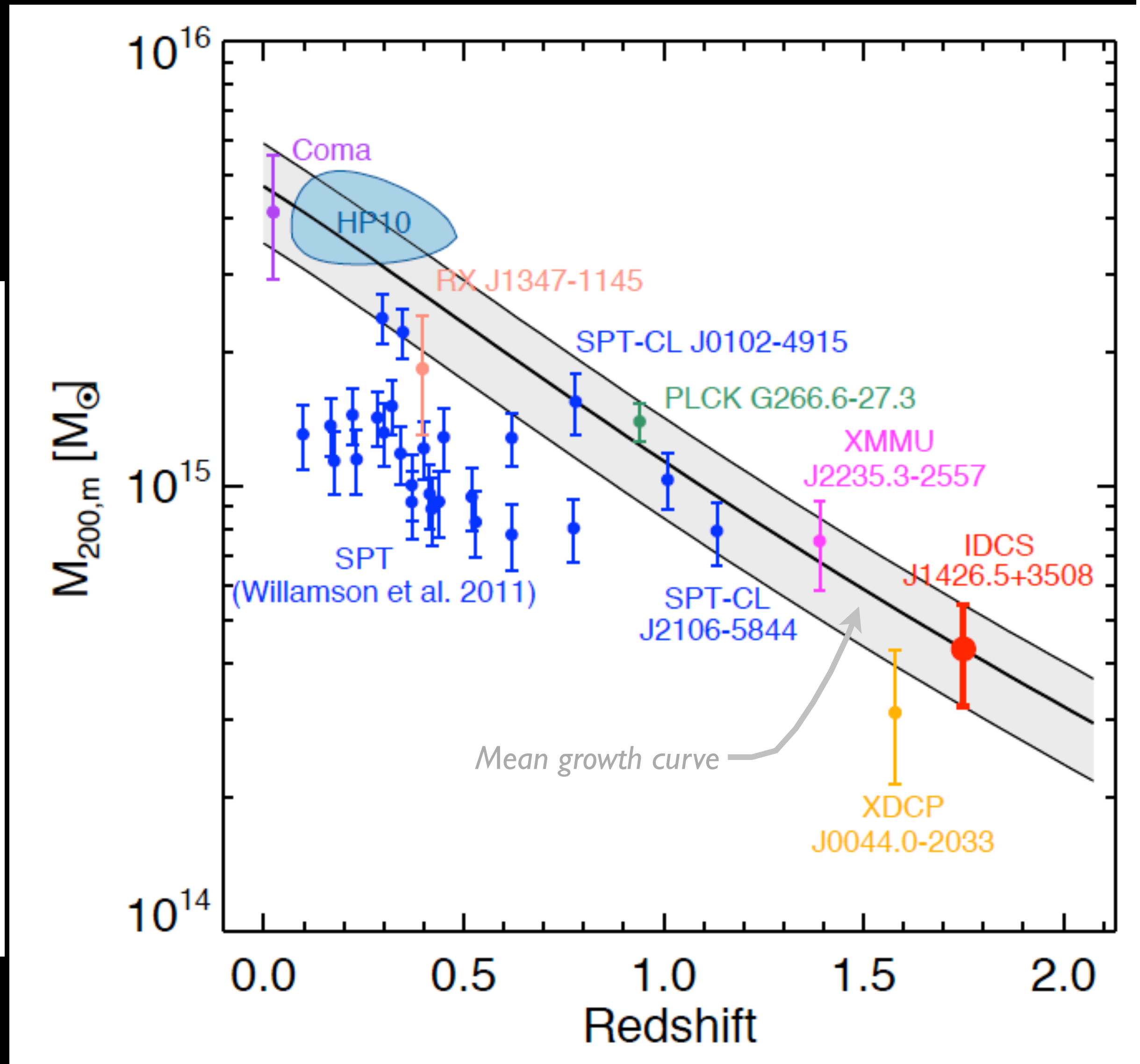
IDCS J1426.5+3508: Rarity and Future Growth

How rare is this cluster?

The mass is extreme, but not inconsistent with LCDM.



Brodwin+ (2012)



IDCS J1426.5+3508: The Arc Statistics Puzzle

How rare is this cluster?

The lensing is a different story...

Number of arcs all sky

$$N_{Arcs}(m) = 4\pi n_S(m) \int_{z_L}^{\infty} p(z_s, m)\tau(z_s)\mathrm{d}z_s$$

Background Galaxy Density

Redshift Distribution for Background Galaxies

Optical Depth

$$\tau(z_S) = \frac{1}{4\pi D_s} \int_{z_L}^{z_S} \mathrm{d}z \int_0^{\infty} \mathrm{d}M n(M, z) \left|\frac{\mathrm{d}V}{\mathrm{d}z}\right| \sigma(M, z)$$

Cluster Mass Function

Cross section (Efficiency for Lensing)

Inputs:

Background galaxy distribution: HUDF distribution

Cluster mass function: Tinker

Cross section: Semi-analytic prescription from Fedeli et al. (2006)

IDCS J1426.5+3508: The Arc Statistics Puzzle

How rare is this cluster?

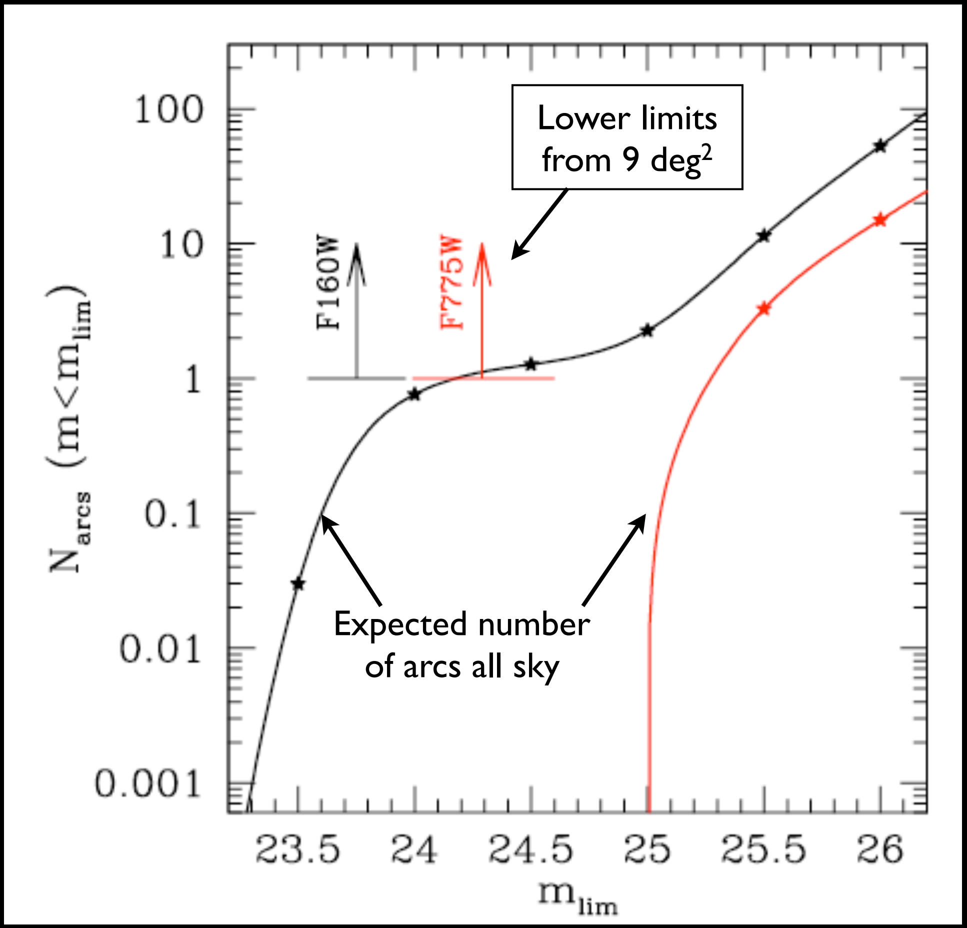
The lensing is a different story...

Possible Explanations

Source redshift distribution

Clusters more concentrated than theoretical halos.

Primordial Non-Gaussianity



Gonzalez+ (2012)

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Will help, but not enough…

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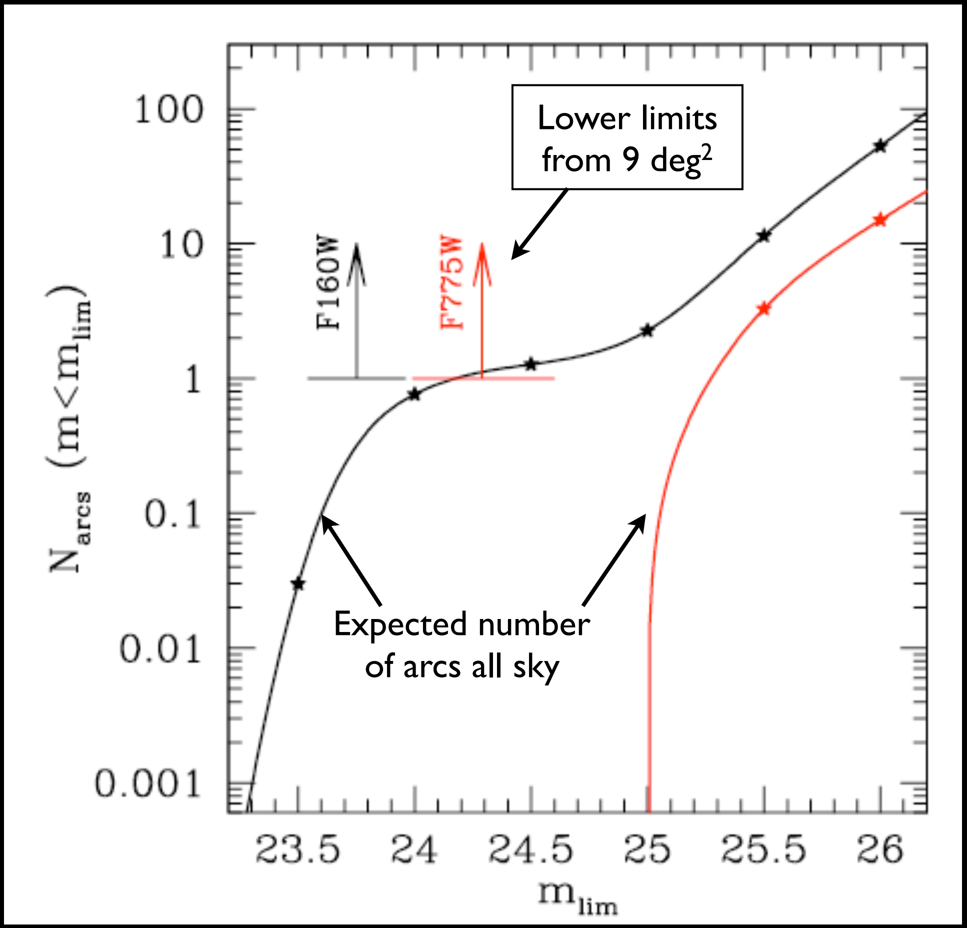
Perhaps (not?)…



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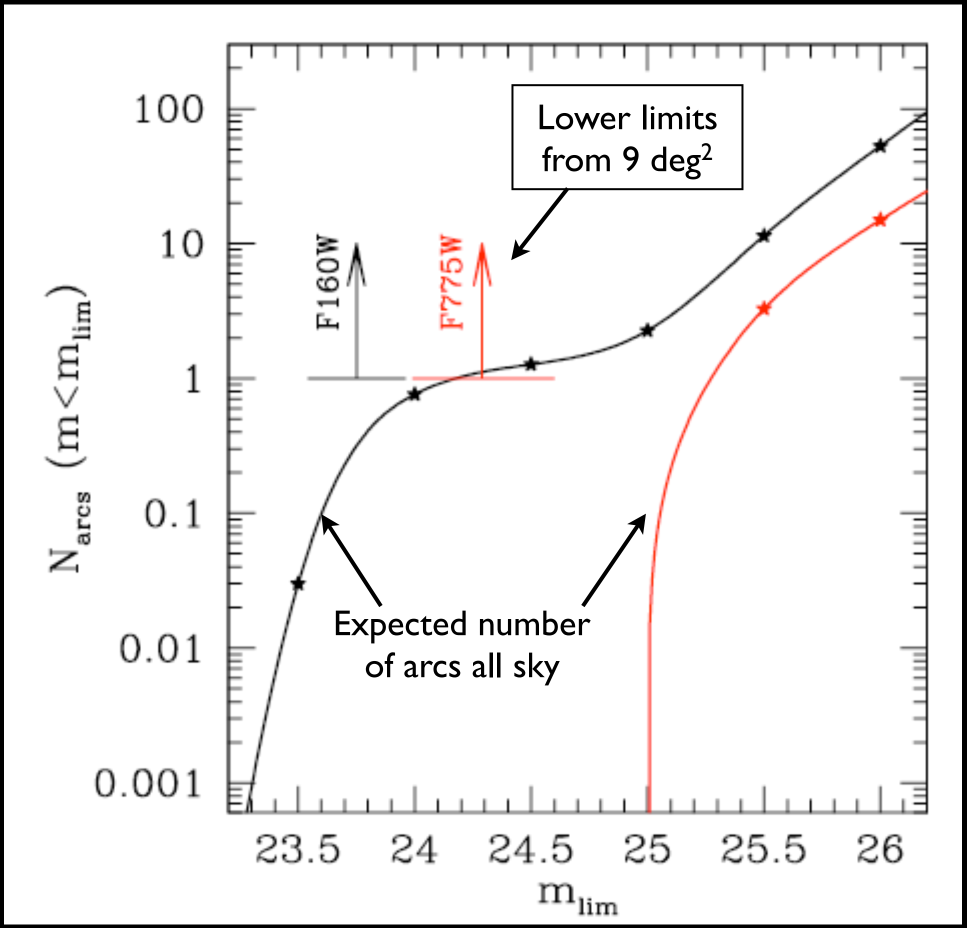
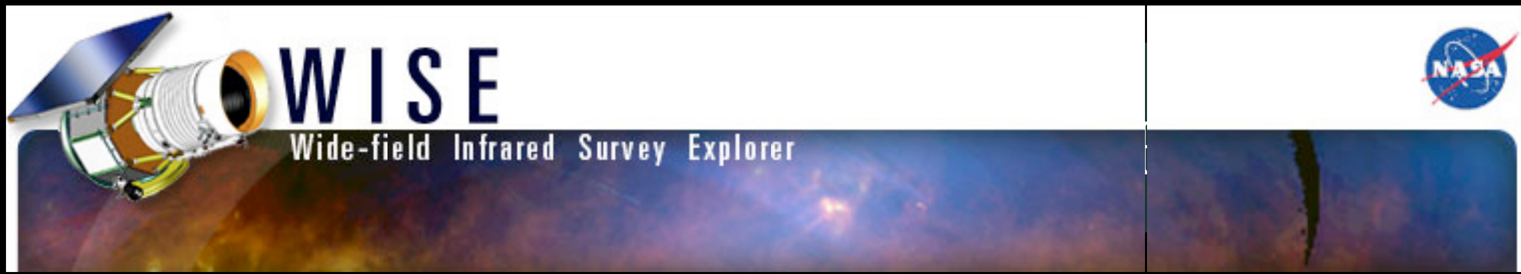


Gonzalez+ (2012)

What are the prospects for larger samples of very massive clusters?



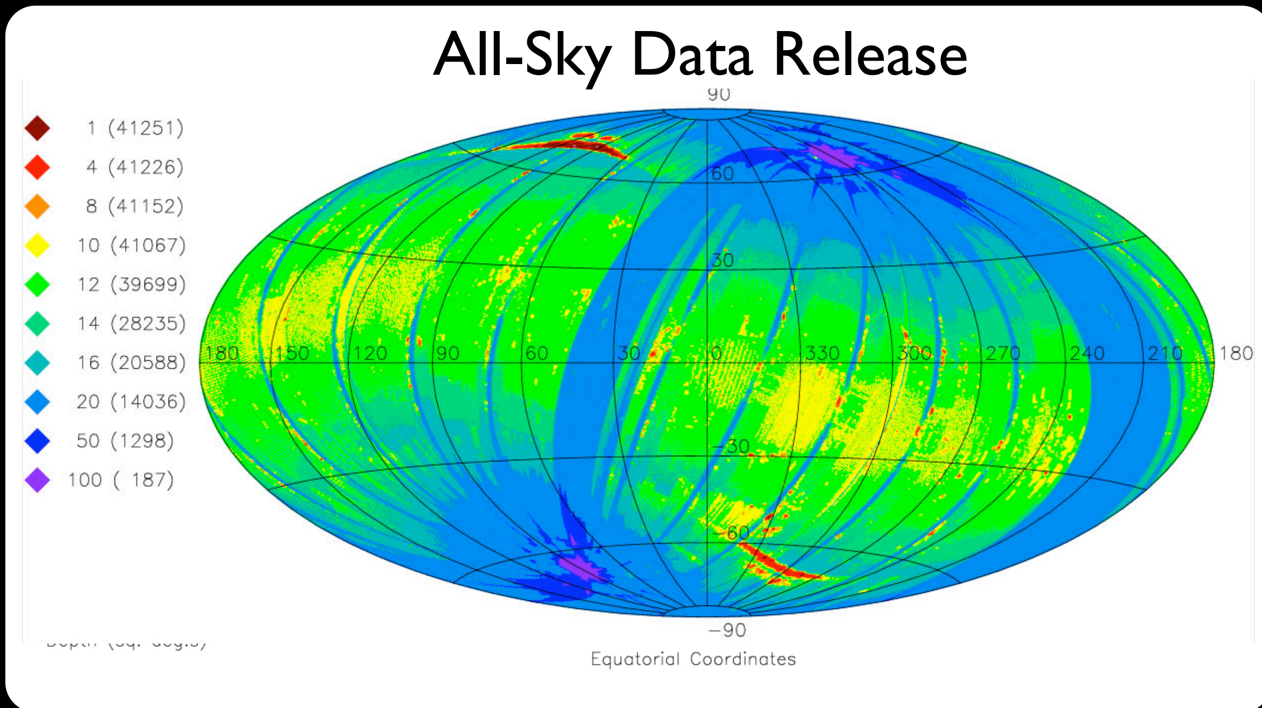
Spitzer is efficient for finding high-z clusters.

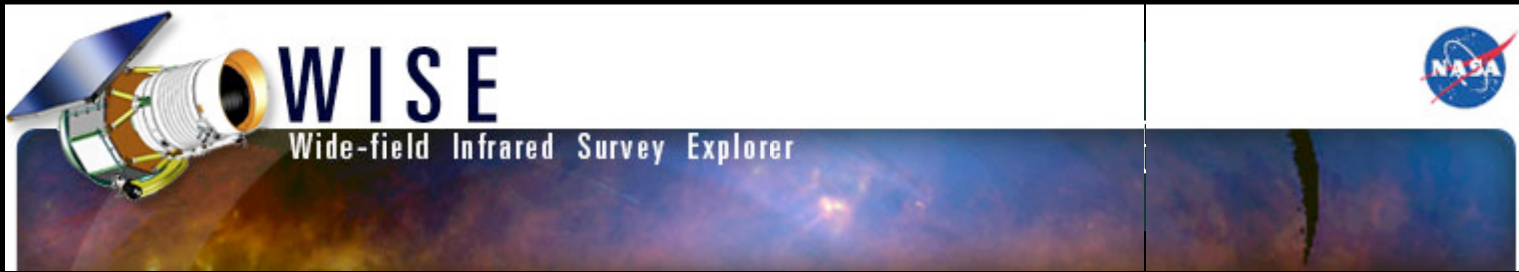
✔ **large redshift reach**

✔ **sensitive down to low masses**

✘ **limited area**

- Coverage
  - All-sky
  - Full release on March 14, 2012
- Wavelengths
  - 3.4, 4.6, 12, and 22 mm
  - 6.1, 6.4, 6.5, 12.0" spatial resolution
- Depth
  - 5σ point source sensitivities better than 0.08, 0.11, 1, and 6 mJy (Wright+ 2010)





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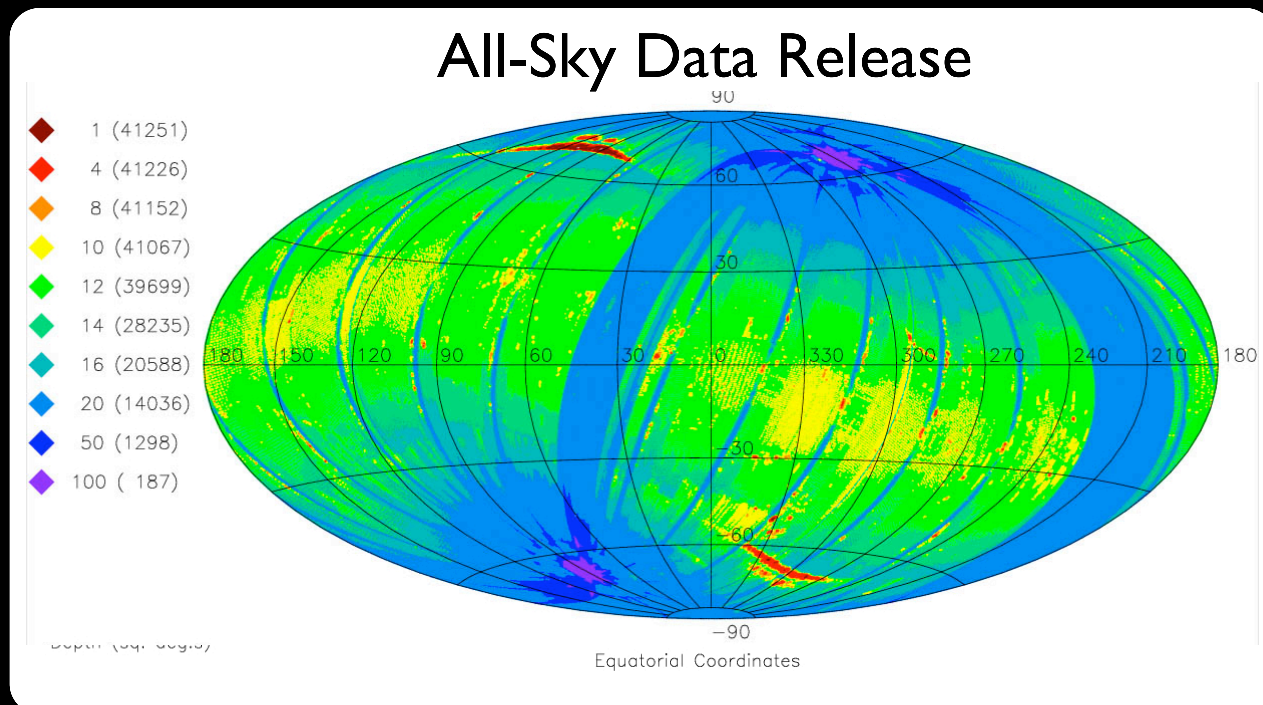
What can we do with WISE?

✘ limited sensitivity and poor spatial resolution

✔ sensitive to the most massive clusters

✔ all sky

- Coverage
  - All-sky
  - Full release on March 14, 2012
- Wavelengths
  - 3.4, 4.6, 12, and 22 mm
  - 6.1, 6.4, 6.5, 12.0" spatial resolution
- Depth
  - 5σ point source sensitivities better than 0.08, 0.11, 1, and 6 mJy (Wright+ 2010)

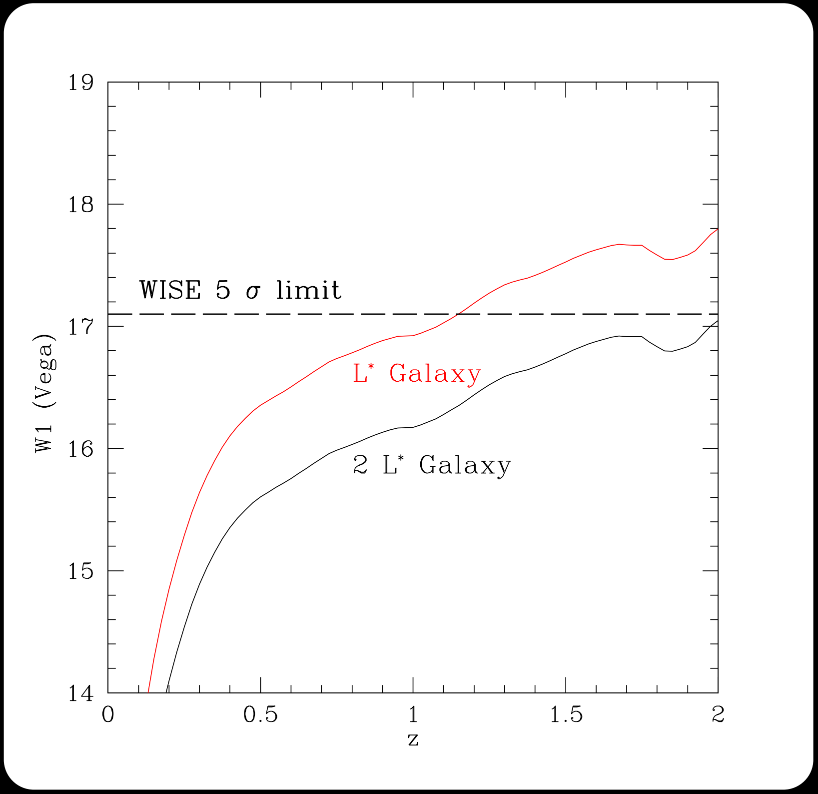


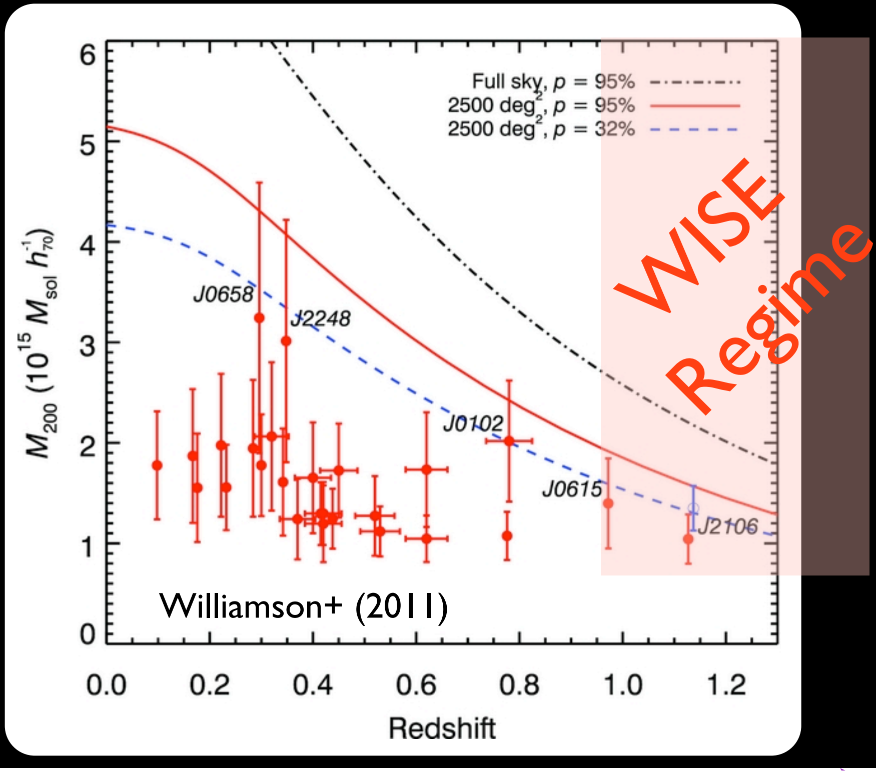
A WISE View of Galaxy Clusters

How high-redshift can one really go with WISE?

- **L^* to z>1.1 (2 L^* to z~2)**
- **overdensities of >L^* galaxies should be visible to z~1.4-1.5**

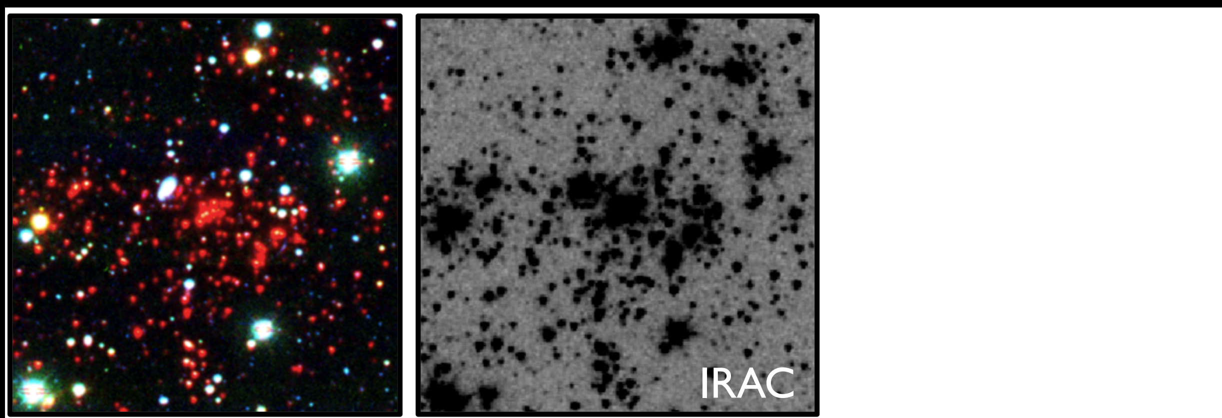
Can provide complement to SZ search for massive clusters as cosmological probe.





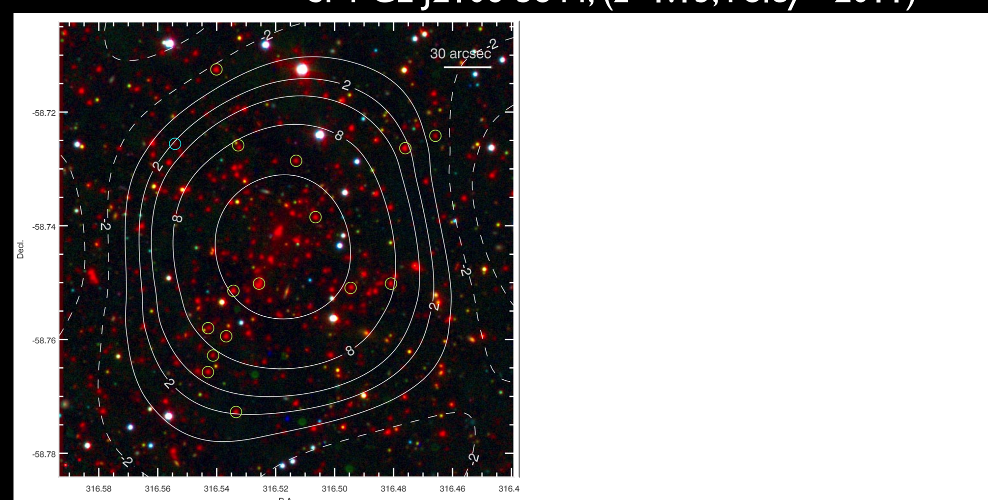
A WISE View of Galaxy Clusters

SPT Clusters as a Test Case



SPT-CL J0546-5345 (z=1.06; Brodwin+ 2011)

SPT-CL J2106-5844, (z=1.13; Foley+ 2011)



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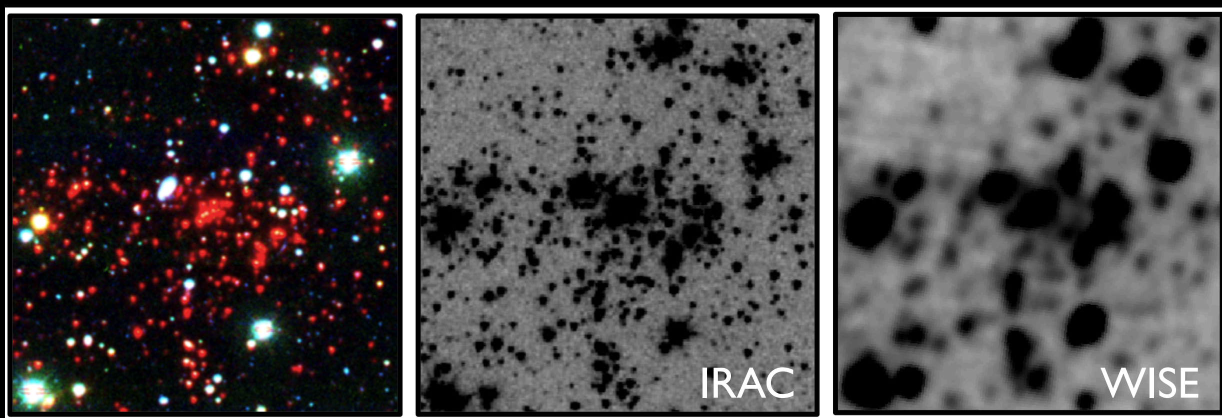

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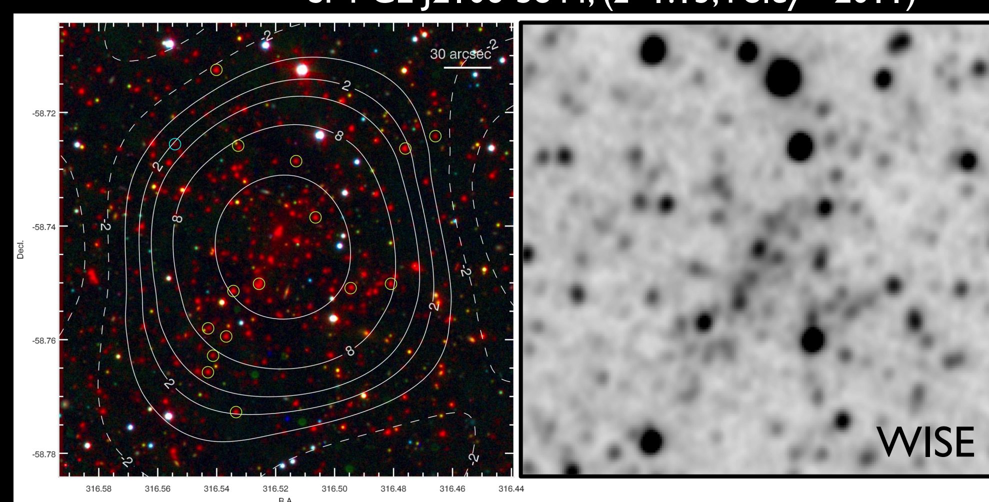
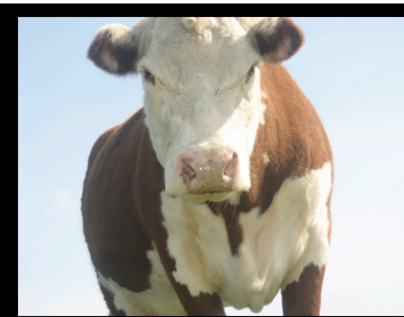


Significant blending, but clusters remain visible.

A WISE View of Galaxy Clusters



The Massive Distant Clusters of WISE Survey (MaDCoWS)

Cluster Detection

Approach: Simple color selection algorithm

- Start with >7s WISE sources
- Reject optically bright sources
- Simple W1-W2 color cut
- Identify overdensities in wavelet-smoothed map

Northern Hemisphere (WISE + SDSS DR8):

-[3.4]-[4.6]>0.2 (Vega)

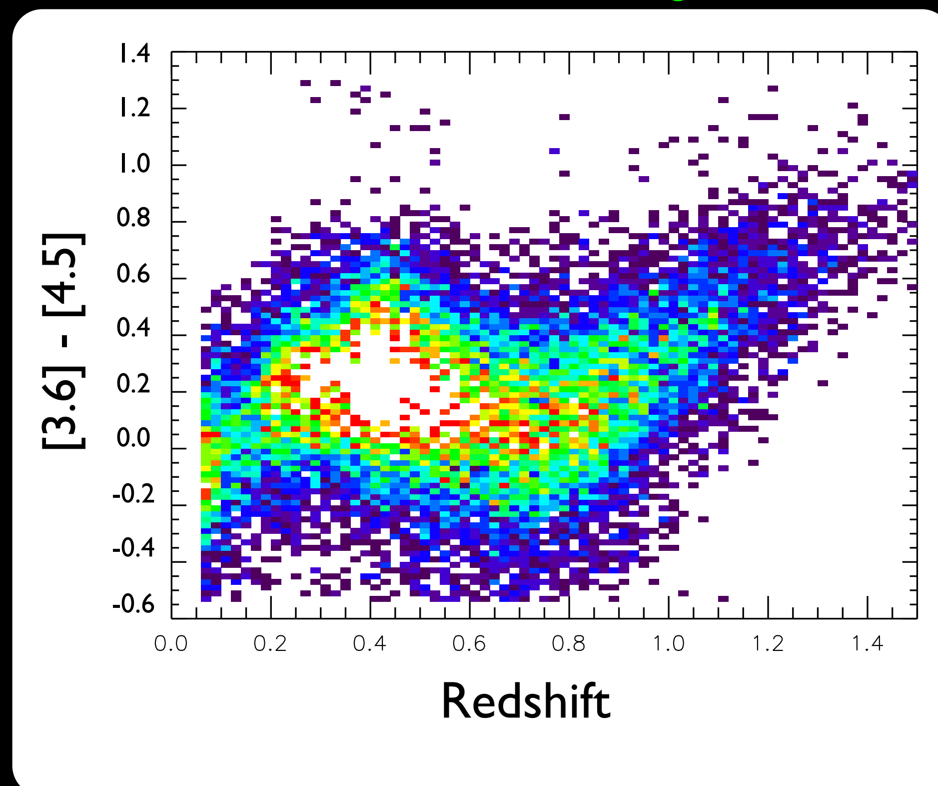
- i>21

Southern Hemisphere (WISE + SuperCOSMOS):

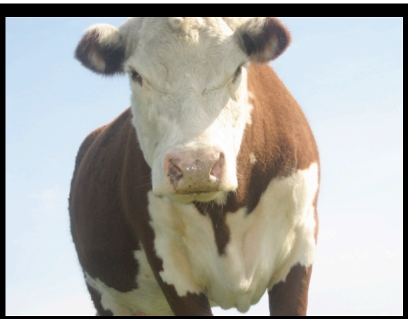
- [3.4]-[4.6]>0.5 (Vega) *redder, higher-z cut*

- R>20.5

WISE colors of SDWFS galaxies



A WISE View of Galaxy Clusters



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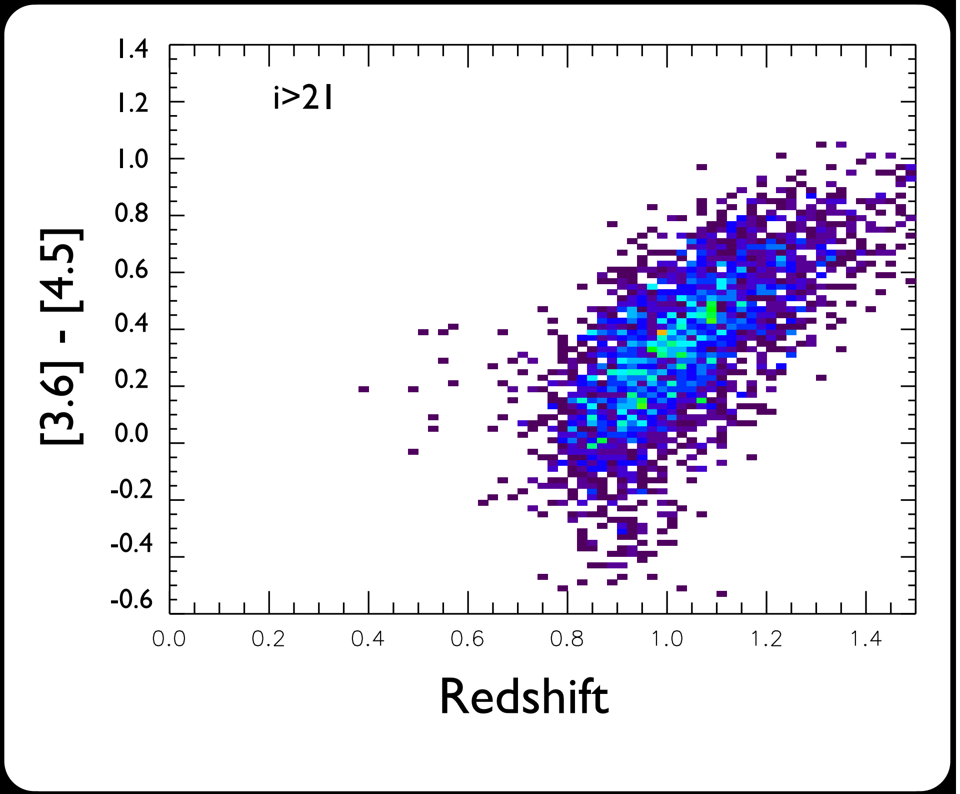

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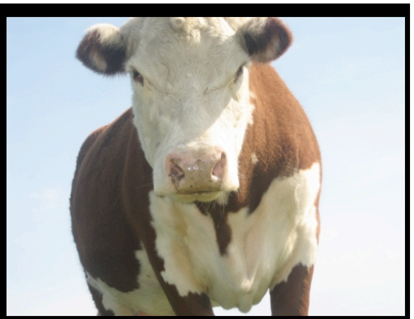

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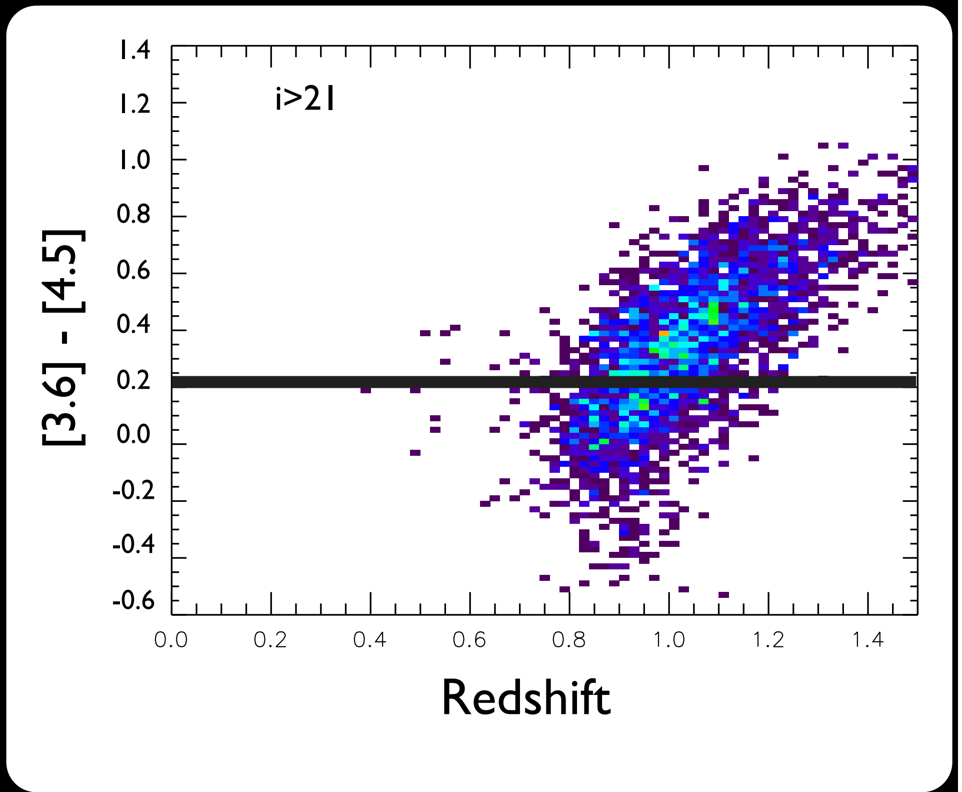
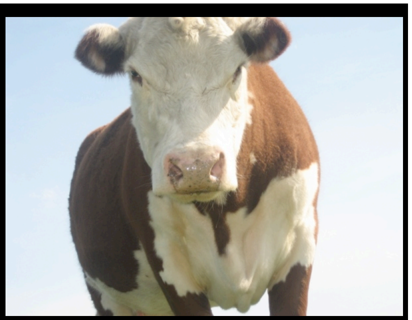


A WISE View of Galaxy Clusters



The Massive Distant Clusters of WISE Survey (MaDCoWS)

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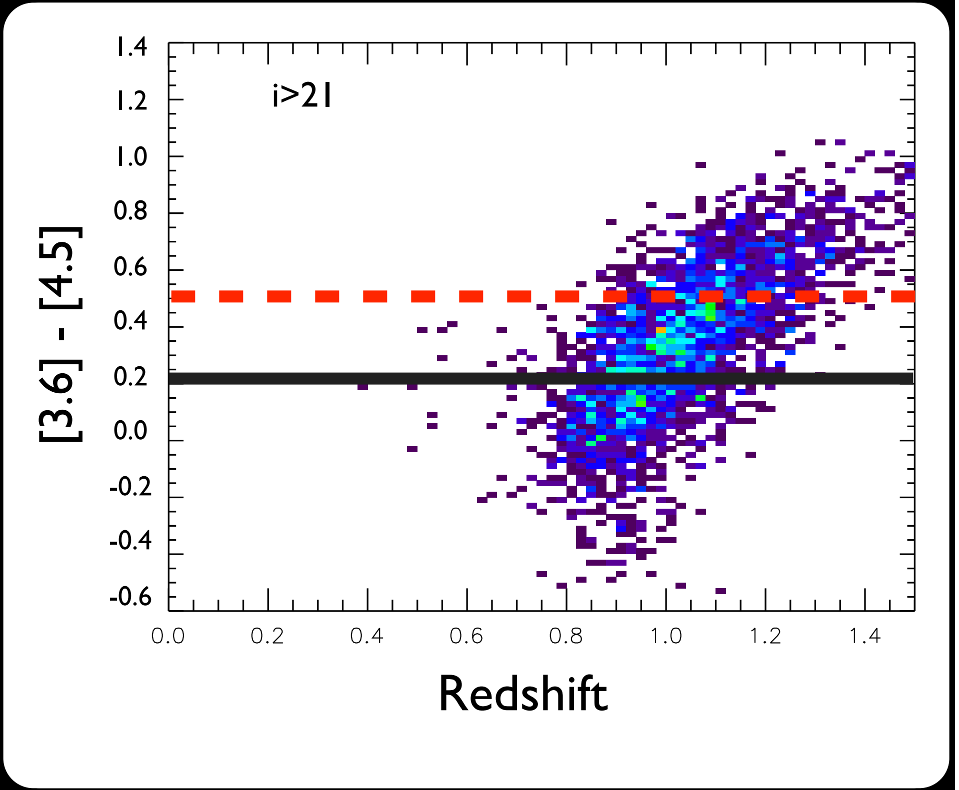
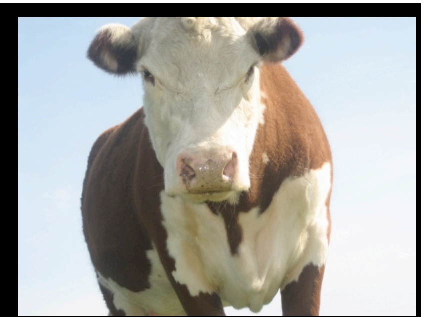
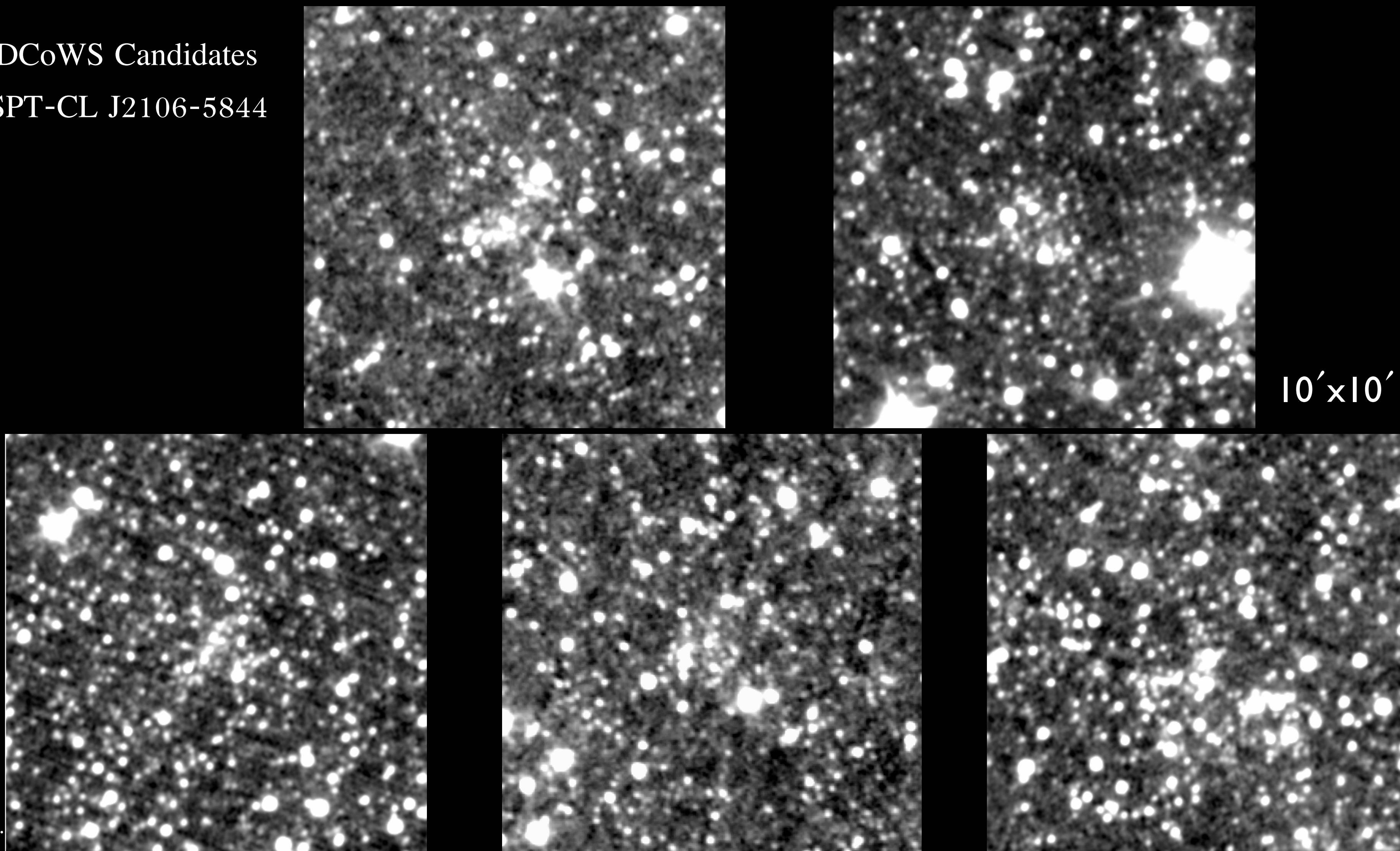


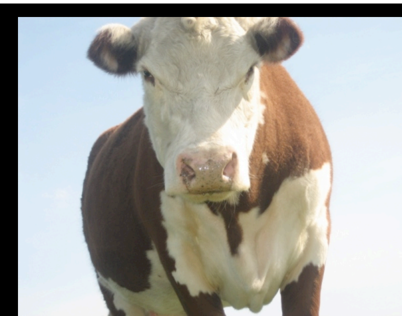
A WISE View of Galaxy Clusters



MaDCoWS

MaDCoWS Candidates
& SPT-CL J2106-5844





A WISE View of Galaxy Clusters

MaDCoWS

MaDCoWS Candidates

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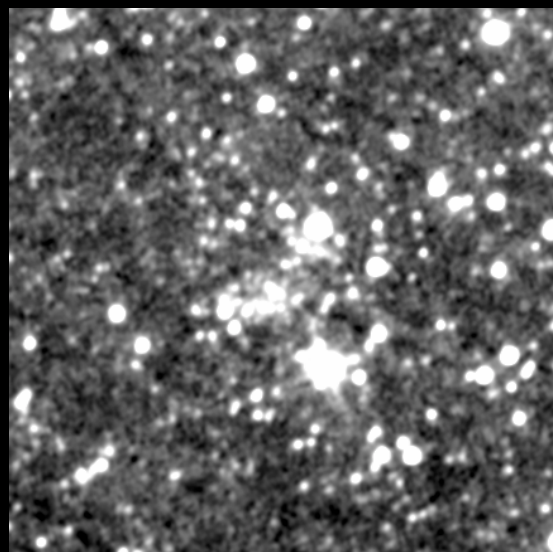
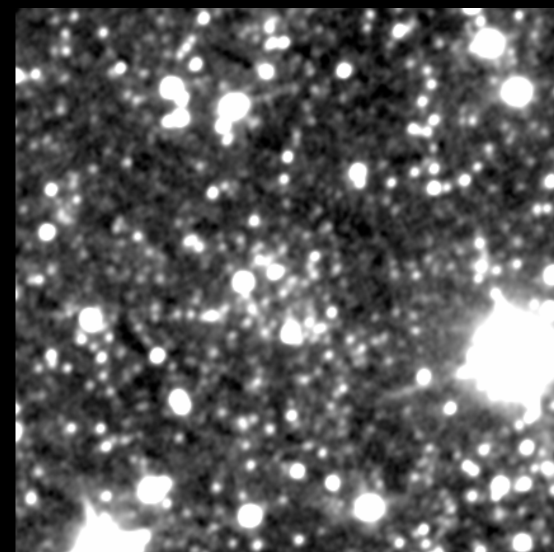
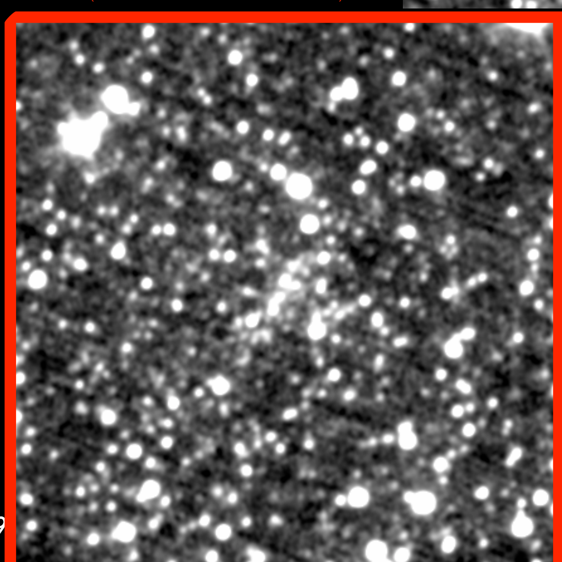
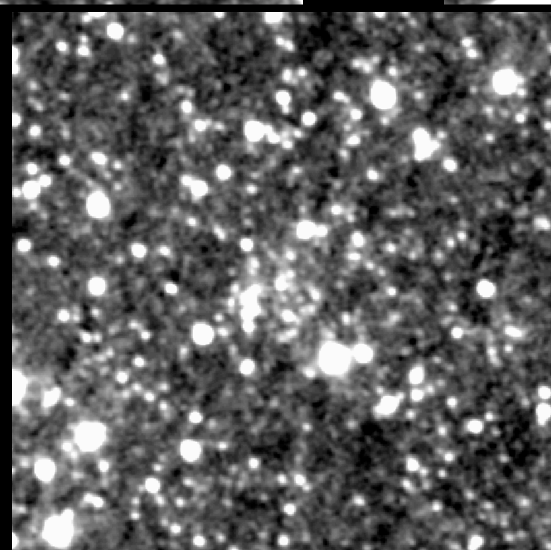


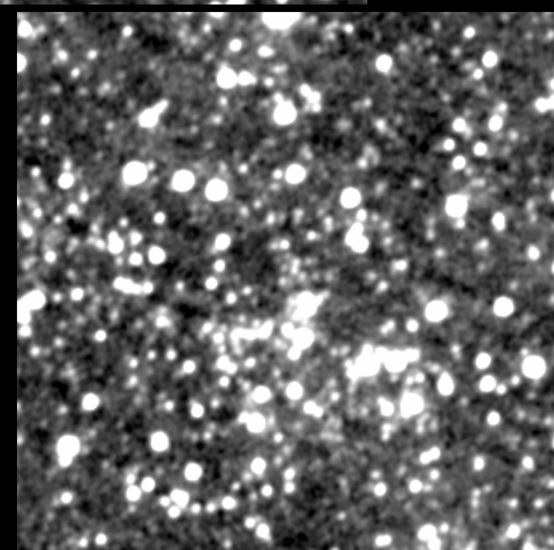


SPT (M=1.7x10^{15} M$_{\odot}$)

10′x10′

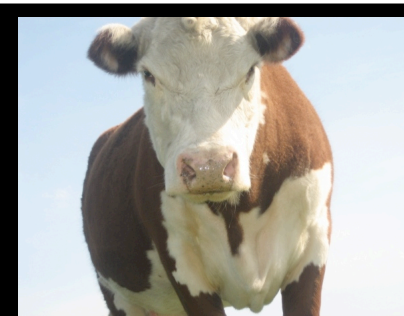






JPL 8.9

A WISE View of Galaxy Clusters



MaDCoWS

MaDCoWS Candidates

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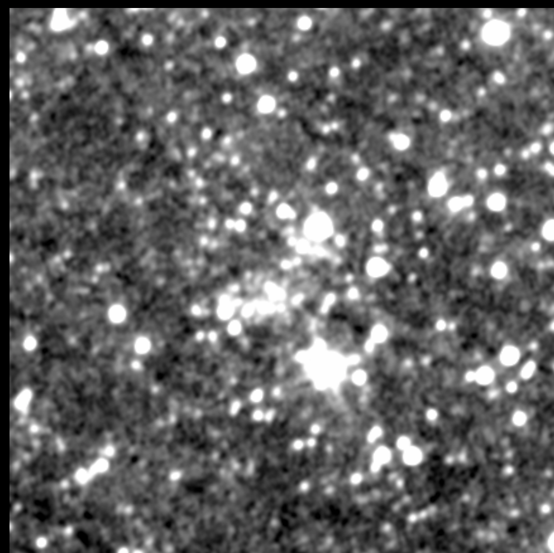
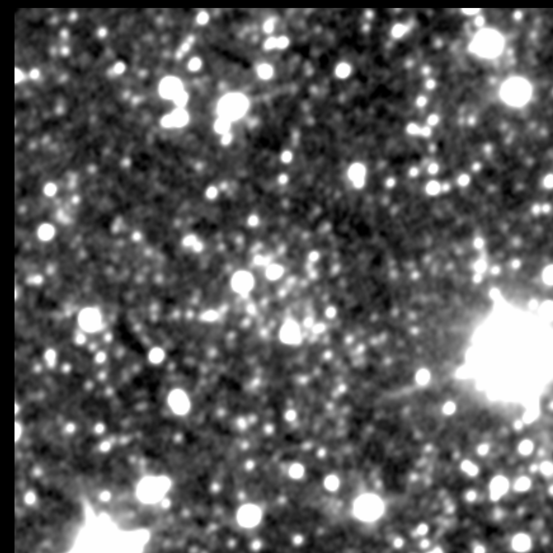
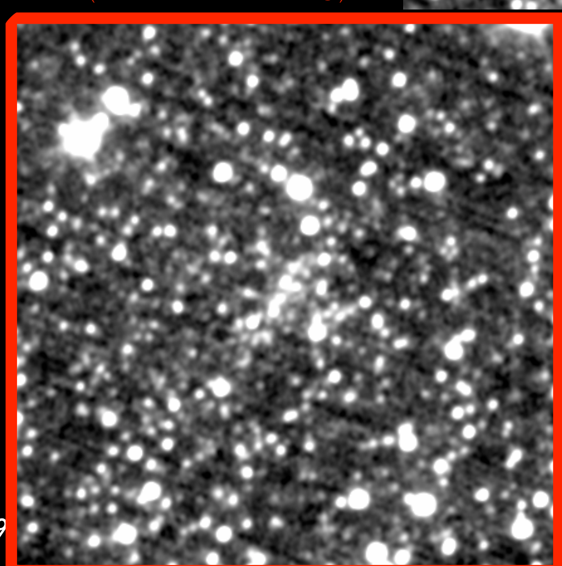
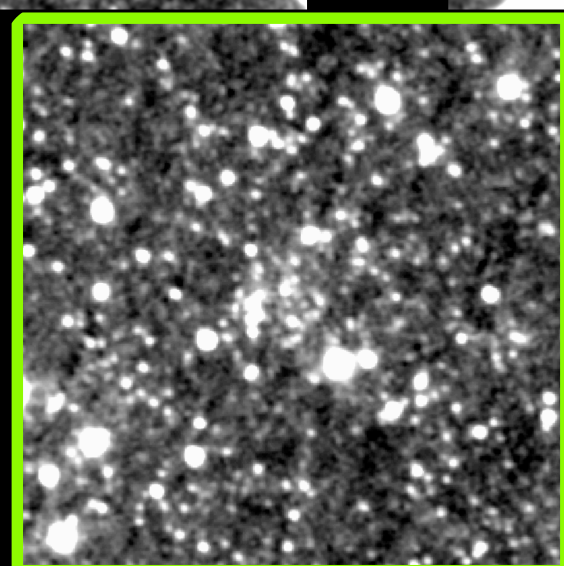


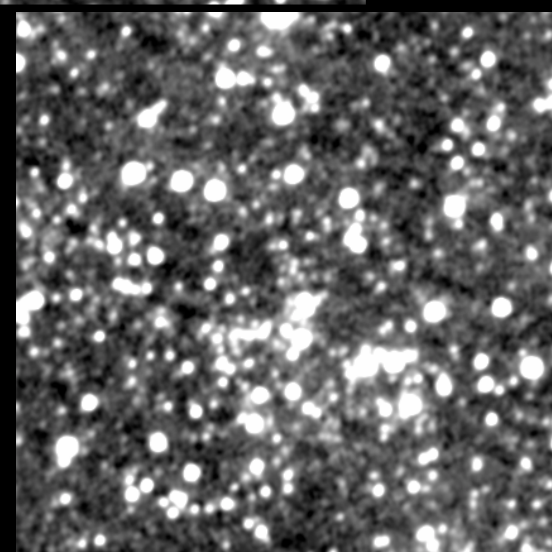


10′x10′

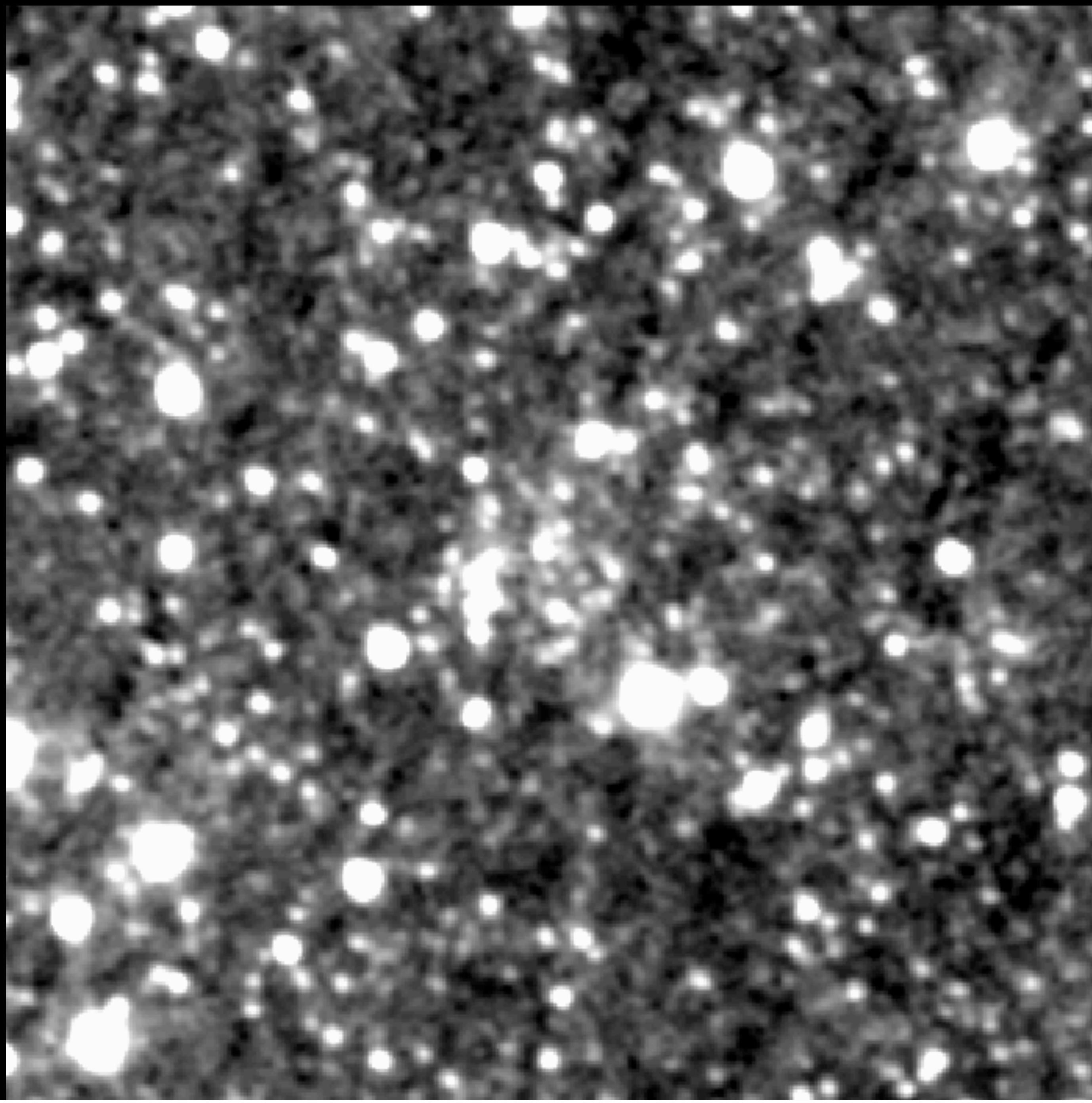
SPT ($M=1.7 \times 10^{15}$ $M_{\odot}$)







MOO J2342+1301 (Bessie)

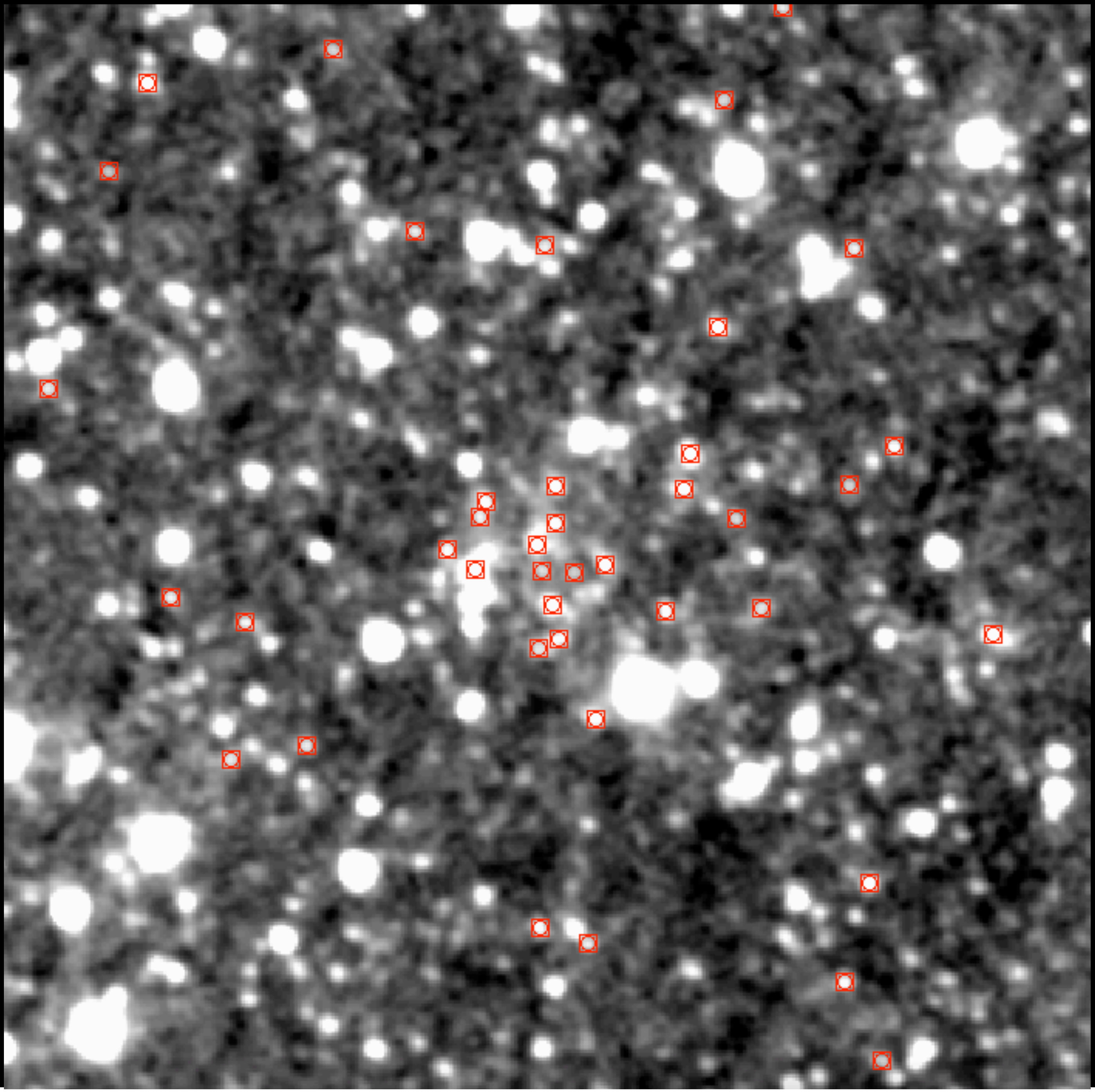


WISE [3.4]

10′x10′

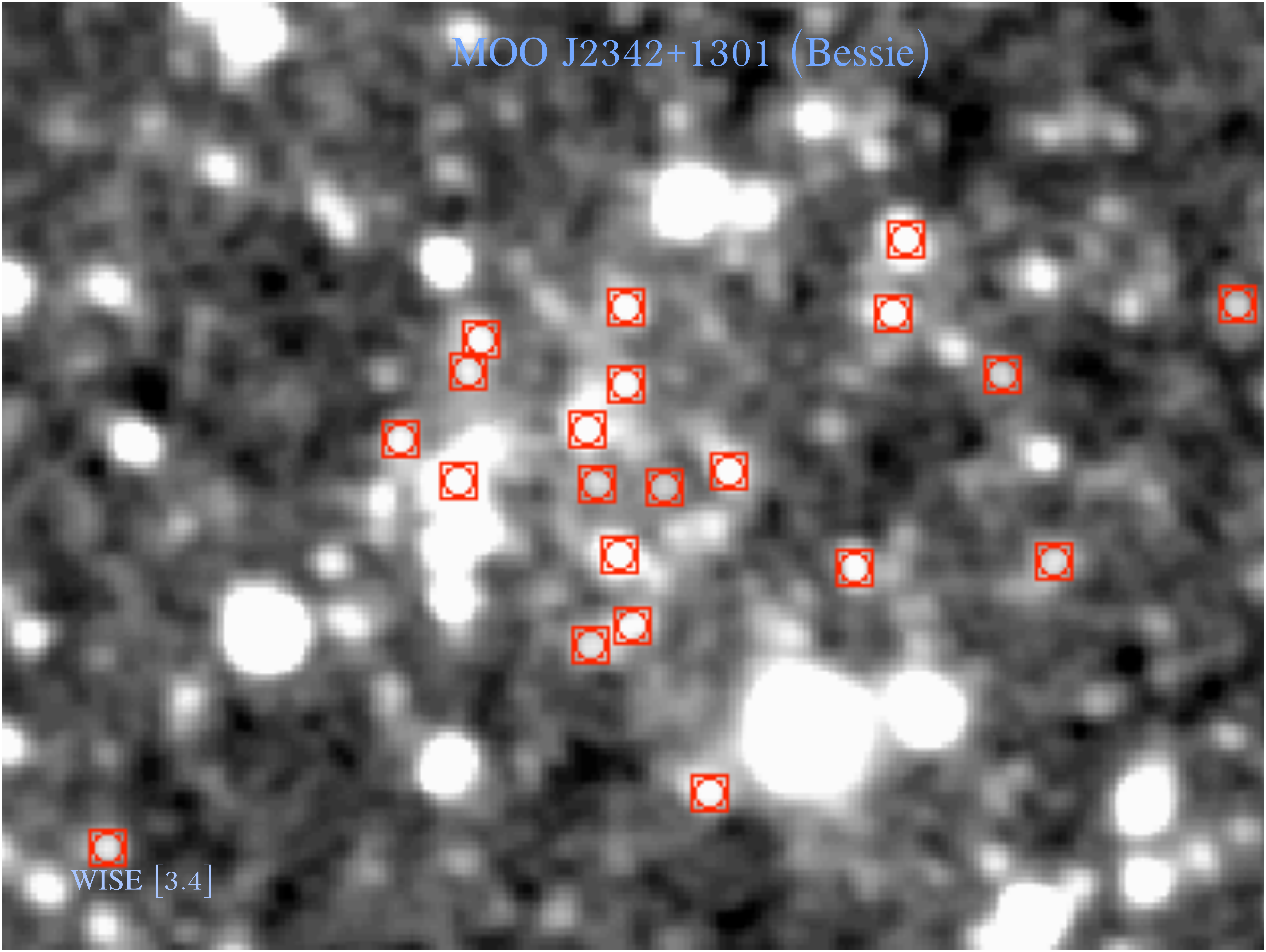
MOO J2342+1301 (Bessie)

Galaxies contributing to detection



WISE [3.4]

10′x10′


MOO J2342+1301 (Bessie)
WISE [3.4]

MOO J2342+1301 (Bessie)

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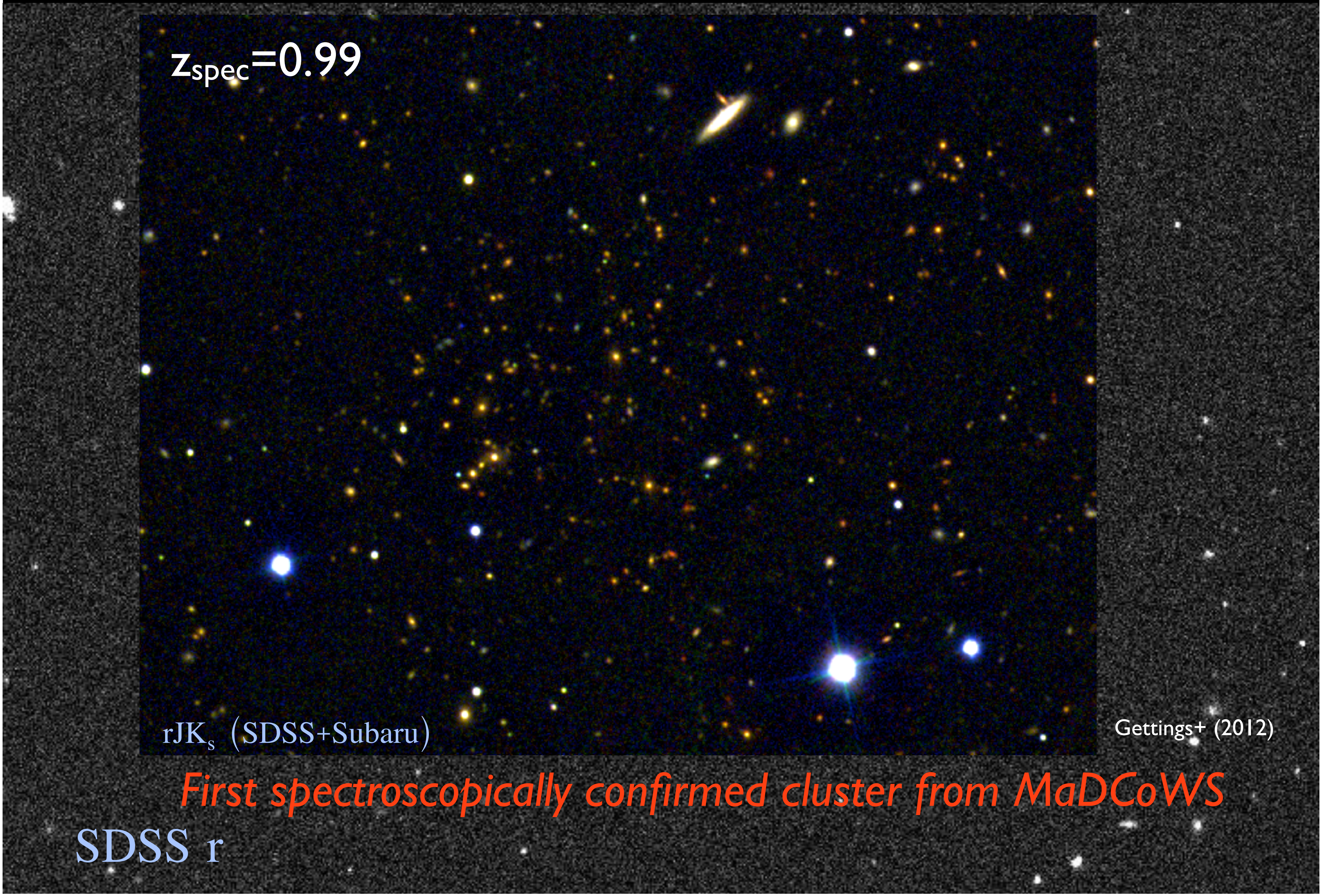
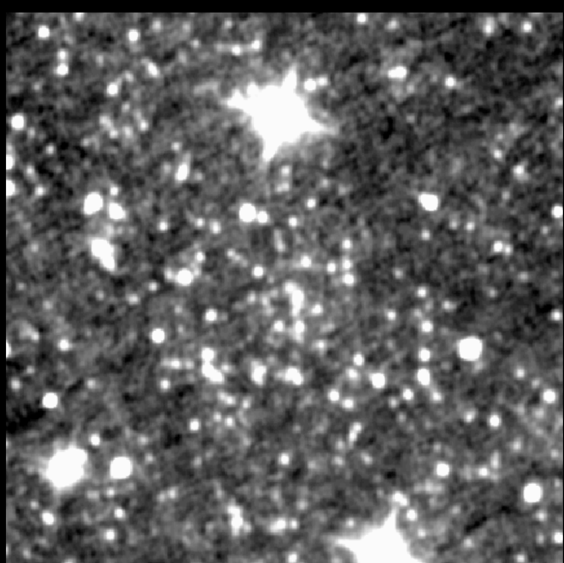
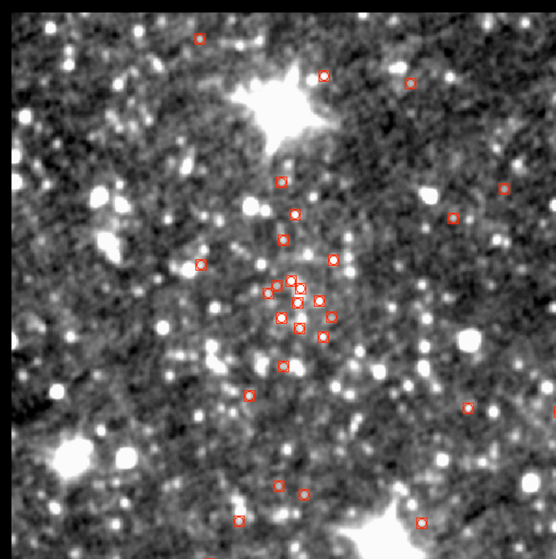


First spectroscopically confirmed cluster from MaDCoWS

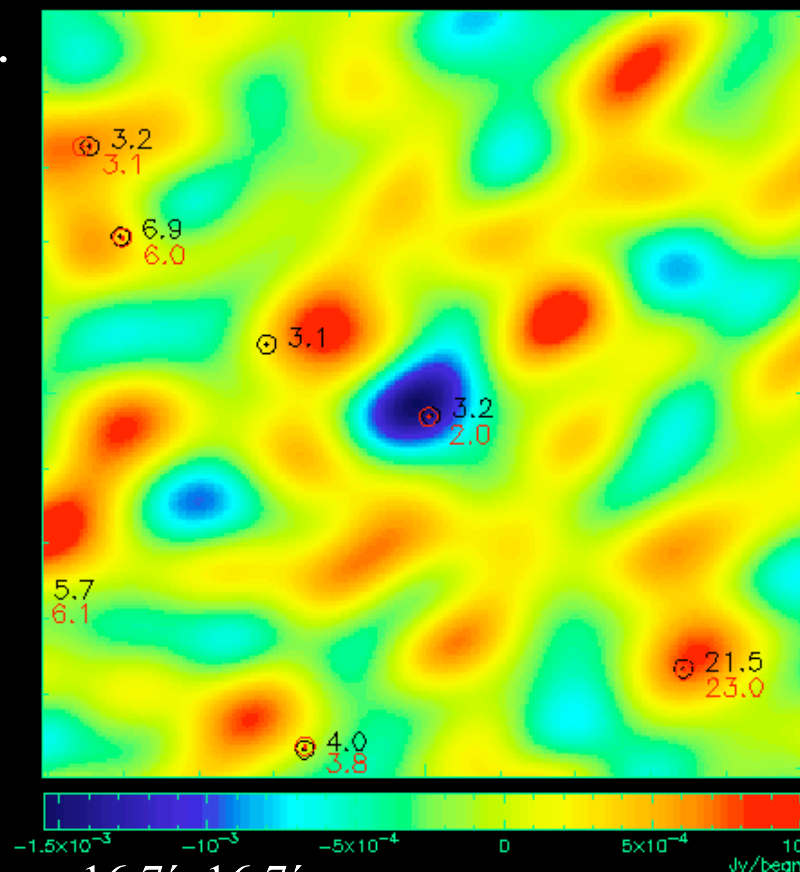
CARMA SZ follow-up in progress for first candidates.

- Fundamental test of how well we are doing.
- First SZ confirmation in hand (3σ).





10′x10′



16.7′x16.7′

Summary

IRAC Cluster Surveys

- IRAC Shallow Cluster Survey (ISCS) *Complete*
    - 300+ clusters and groups; 100+ at z>1
    - Evidence for significant mass assembly and star formation at z>1.3 (luminosity function and red sequence)
    - Red sequence evolution consistent with continuous evolution of galaxies onto red sequence until z~1.3 with ~1 Gyr delay after star formation ceases
- IRAC Distant Cluster Survey (IDCS) *In progress*
    - Extension of ISCS to lower mass and higher redshift
    - Several confirmed clusters at 1.5<z<1.9
    - $5 \times 10^{14}\ M_\odot$ strong lensing cluster at z=1.75

      …interesting new challenge to understand…

WISE Cluster Surveys

- Massive Distant Clusters of WISE *In progress*
    - First all-sky survey for z>1 clusters
    - Efficient detection of the most massive clusters at z≃1–1.5
    - Search complete, follow-up underway
    - Stay tuned.